Vol. XXII.—No. 125] [June, 1929.

THE

MINERALOGICAL MAGAZINE

AND

Journal of

The Mineralogical Society

(*INSTITUTED FEBRUARY 3, 1876.*)

WITH A SEPARATELY-PAGED APPENDIX OF

MINERALOGICAL ABSTRACTS

EDITED BY L. J. SPENCER, F.R.S.

ABSTRACTORS

F. N. ASHCROFT.
F. A. BANNISTER.
H. E. BUCKLEY.
P. N. CHIRVINSKY.
T. CROOK.
A. F. HALLIMOND.
M. H. HEY.
HAROLD HILTON.
E. D. MOUNTAIN.
A. L. PARSONS.
G. T. PRIOR.
W. A. RICHARDSON.
S. J. SHAND.
F. SLAVÍK.
W. CAMPBELL SMITH.
L. J. SPENCER.
K. ZIMÁNYI.

LONDON:
HUMPHREY MILFORD, OXFORD UNIVERSITY PRESS,
AMEN HOUSE, WARWICK SQUARE, E.C. 4.

1929.

Price 6s. net.
Annual Subscription for four numbers, Post free 20s.

MINERALOGICAL SOCIETY

Officers and Council for 1928–29.

PRESIDENT.

G. T. Prior, M.A., D.Sc., F.R.S.

PAST-PRESIDENTS.

Sir Henry A. Miers, M.A., D.Sc., LL.D., F.R.S. (1904–1909).
A. E. H. Tutton, M.A., D.Sc., F.R.S. (1912–1915).
W. Barlow, F.R.S. (1915–1918).
Prof. A. Hutchinson, O.B.E., M.A., Ph.D., F.R.S. (1921–24).
Prof. W. W. Watts, M.A., M.Sc., Sc.D., LL.D., F.R.S. (1924–27).

VICE-PRESIDENTS.

Sir J. S. Flett, K.B.E., M.A., LL.D., D.Sc., F.R.S.
J. W. Evans, C.B.E., LL.B., D.Sc., F.R.S.

TREASURER.

F. N. Ashcroft, M.A., F.G.S., F.C.S., 1 *Egerton Gardens, South Kensington, London, S.W.* 3.

GENERAL SECRETARY.

W. Campbell Smith, M.C., M.A., F.G.S., *Natural History Museum, South Kensington, London, S.W.* 7.

FOREIGN SECRETARY.

J. W. Evans, C.B.E., LL.B., D.Sc., F.R.S., *Imperial College of Science and Technology, South Kensington, London, S.W.* 7.

EDITOR OF THE JOURNAL.

L. J. Spencer, M.A., Sc.D., F.R.S., *Natural History Museum, South Kensington, London, S.W.* 7.

TRUSTEES.

F. N. Ashcroft, M.A., F.G.S., F.C.S.
Sir Henry A. Miers, M.A., D.Sc., LL.D., F.R.S.

ORDINARY MEMBERS OF COUNCIL.

Col. N. T. Belaiew, C.B., F.C.S.
Prof. H. L. Bowman, M.A., D.Sc., F.G.S.
A. J. Bull, M.Sc., F.Inst.P., F.G.S.
H. Collingridge, B.Sc., F.G.S.
Prof. C. G. Cullis, D.Sc., F.G.S.
Henry Dewey, F.G.S.
Prof. W. T. Gordon, M.A., D.Sc., F.R.S.E.
H. F. Harwood, M.Sc., Ph.D., A.I.C.
Prof. Harold Hilton, M.A., D.Sc.
Prof. Arthur Holmes, D.Sc., F.G.S.
W. F. P. McLintock, D.Sc., F.G.S.
G. F. Herbert Smith, M.A., D.Sc., F.G.S.

LIBRARIAN.

Miss J. M. Sweet, B.Sc., *Natural History Museum, South Kensington, London, S.W.* 7 (to which address all publications intended for the Library of the Society should be forwarded).

Bankers.—Messrs. Coutts & Co., 15 *Lombard Street, London, E.C.* 3.

THE MINERALOGICAL MAGAZINE
AND
JOURNAL OF
THE MINERALOGICAL SOCIETY

No. 125. June, 1929. Vol. XXII.

On larnite (calcium orthosilicate, a new mineral) and its associated minerals from the limestone contact-zone of Scawt Hill, Co. Antrim.

By C. E. Tilley, B.Sc., Ph.D., F.G.S.
Department of Geology, University of Cambridge.

[Read March 15, 1927, and January 17, 1928.]

THE contact-zone of Chalk and Tertiary dolerite at Scawt Hill, near Larne, Co. Antrim, consists of an assemblage of comparatively rare minerals, including a mineral of the composition Ca_2SiO_4 not previously recognized as a naturally occurring compound. In the assemblages of the contact-zone the chief minerals, apart from calcite, are spurrite, calcium orthosilicate (larnite), melilite (gehlenite), merwinite, spinel, perovskite, and wollastonite. Outside this contact-zone, the chalk consists almost wholly of calcium carbonate; nearer the contact it is recrystallized to a granular mosaic of calcite of coarse texture, while at the immediate contact the chalk is completely transformed into an aggregate of new-formed silicates in varying proportions. A hybrid zone between the dolerite and the exogenous contact-rock is composed of a coarsely crystalline rock built up essentially of titanaugite, melilite (humboldtilite), nepheline, wollastonite, perovskite, and various zeolites. An account of the melilite of this hybrid zone has already been given.[1] The present note deals particularly with the assemblages forming the exogenous contact-zone that have resulted by metamorphism and metasomatism

[1] C. E. Tilley, Geol. Mag., 1929, vol. 66.

of the chalk. A preliminary notice on the constitution of this zone was given in 1927.[1]

The rocks of the contact-zone of Scawt Hill were described as long ago as 1907 by G. C. Gough,[2] but this account is unfortunately largely erroneous. The figures accompanying his paper are sufficiently clear to allow of their reinterpretation, e. g. plate v, fig. 3 is a photomicrograph showing in addition to calcite idiomorphic crystals of spurrite. Larnite is also probably represented.

The chief assemblages of the contact-zone are the following:

(*a*) Spurrite
(*b*) Spurrite-larnite
(*c*) Spurrite-larnite-melilite (gehlenite)
(*d*) Spurrite-melilite (gehlenite)-merwinite-spinel-larnite
} calcite.

There is thus a considerable range of rock type, from assemblages rich in spurrite and larnite respectively to those rich in spinel with minor spurrite. Some rock types are also rich in merwinite.

(1) *Spurrite* ($2\,Ca_2SiO_4.CaCO_3$) is the most prominent mineral of the contact-zone, where it forms the essential component of the rock. It occurs usually as a finely crystalline mass of white colour with a vitreous, inclining to resinous, lustre. On fractured surfaces larger crystals reaching up to half an inch in length may occur. They are then elongated and show a well-marked cleavage. Spurrite is most commonly associated with more finely crystallized larnite (fig. 4). The mineral is readily attacked by hydrochloric acid with evolution of carbon dioxide and leaves a gelatinous residue of silica.

Under the microscope, spurrite is distinguished by its imperfect cleavage, high birefringence, and polysynthetic twinning. The optical properties are as follows: α 1·640, γ 1·680, double refraction negative, and small optic axial angle (2V 40°). The twinning is parallel to the dominant cleavage, a poor second cleavage at angles of 79–80° being also observed. Sections perpendicular to the acute bisectrix show symmetrical extinction of adjacent lamellae, and the crystals are frequently elongated in the direction of the twin-lines and the cleavage. As has been shown by Wright[3] the properties of spurrite agree with those of a monoclinic mineral in which $a = b$, the cleavages being parallel to the axis of symmetry. The orientation of the Scawt Hill spurrite is such that in the plane (010)

[1] C. E. Tilley, Min. Mag., 1928, vol. 21, p. xlviii, 1929, vol. 22, p. xxviii; and Geol. Mag., 1927, vol. 64, p. 285.

[2] G. C. Gough, Geol. Mag., 1907, dec. 5, vol. 4, p. 145.

[3] F. E. Wright, Amer. Journ. Sci., 1908, ser. 4, vol. 26, p. 547.

the optic axial plane is inclined 57° to the twin-lines and the cleavage, the vibration-direction β making an angle of 33° with the twinning, with symmetrical extinction of adjacent lamellae. Much less common is a simple twinning on a plane practically parallel to the optic axial plane. These features are in agreement with the figured orientation given by Wright (loc. cit., p. 548), but not with the text description, where it is stated that the orientation is $\gamma = a$, the cleavage being taken parallel to (001).

The orientation of elongated sections perpendicular to the acute bisectrix for polysynthetic twins of spurrite is shown in fig. 1. Sections perpendicular to (010) show high interference-tints and possess straight extinction with reference to the dominant cleavage. If the principal cleavage be taken as (100), the orientation is $a = b$, $\beta : c = 33°$.

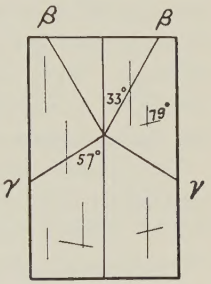


FIG. 1. Optical orientation of spurrite on the plane of symmetry (010).

At the original locality, Velardeña, Mexico, spurrite occurs in association with gehlenite, idocrase, and grossular (also merwinite).[1] It has also been recorded from Riverside, California, here again in association with gehlenite, grossular, merwinite, and monticellite.[2]

(2) *Larnite* (Ca_2SiO_4).—Next in importance to spurrite comes a mineral consisting of calcium orthosilicate. As this is the first recorded natural occurrence[3] of this compound it is proposed to designate it as larnite, from Larne, in the vicinity of which these contact minerals occur.

The texture of the rocks composed essentially of larnite is much finer grained than that of the spurrite rocks. In hand-specimens the larnite-rich rocks are greyish and frequently so close-textured that individual grains cannot be made out by the unaided eye. Even in

[1] C. E. Tilley, Geol. Mag., 1928, vol. 65, p. 372. [Min. Abstr., vol. 4, p. 84.]

[2] W. F. Foshag, Amer. Min., 1920, vol. 5, p. 80; E. S. Larsen and W. F. Foshag, ibid., 1921, vol. 6, p. 143.

[3] The Tasmanian mineral recorded as calcium orthosilicate by F. P. Paul (Tschermaks Min. Petr. Mitt., 1906, vol. 25, p. 309), and named shannonite (C. E. Tilley, Geol. Mag., 1927, vol. 64, p. 144) on the basis of Paul's data, has since been shown to be monticellite (C. E. Tilley, Geol. Mag., 1928, vol. 65, p. 29). Rather than transfer the name 'shannonite' to the mineral now described, any further confusion will be avoided by adopting a new name. [See Min. Mag., 1928, vol. 21, p. 576.]

its purest occurrence, some spurrite is usually found associated with it. Typically, however, the spurrite forms much larger crystals scattered sporadically through the rock; and these contain numerous enclosures of small drop-like grains of larnite (fig. 2).

Optically, the larnite is distinguished from the spurrite by its higher refringence and noticeably lower birefringence. Typically, the larnite forms grains showing one good cleavage and an imperfect cleavage 90° thereto. The most characteristic feature of this mineral is exceedingly fine polysynthetic twinning parallel to the prominent cleavage. Much less commonly a second set of twin-lamellae is developed at right angles to the first set. The twinning is usually not made out except under high-power objectives.

The optical properties are as follows: optically positive with a moderately large optic axial angle; α 1·707, β 1·715, γ 1·730, $\gamma - \alpha$ 0·023. Sections cut perpendicular to the acute bisectrix (γ) show a symmetrical extinction of the adjacent lamellae of the very fine polysynthetic twins, the orientation being α: twin-line $= 13 - 14°$. In sections cut perpendicular to the obtuse bisectrix the mineral has straight extinction with reference to the cleavage, and no twin structure is visible. These properties are those of a monoclinic mineral where $\gamma = b$. If the prominent cleavage and twinning are taken as parallel to (100) the orientation is then $\alpha : c = 13 - 14°$.

When the mineral gives indication of crystal habit the grains appear flattened parallel to (010) with prominent clinodome and pyramid faces, but crystal outline is not very well marked.

The larnite is attacked slowly by water with production of $Ca(OH)_2$, the solution turning red litmus blue. It is destroyed readily by the weakest acid (HCl) without effervescence, but with gelatinization. An analysis of material separated from the rock and still containing very small amounts of spurrite, is given below under I.

		I.	Calculated for Ca_2SiO_4.	Calculated for $Ca_3Si_2O_7$.
SiO_2	...	31·00	34·9	41·7
Al_2O_3	...	1·12	—	—
Fe_2O_3	...	trace	—	—
FeO	...	0·64	—	—
MgO	...	0·69	—	—
CaO	...	64·98	65·1	58·3
CO_2	...	0·82	—	—
$H_2O+105°$	...	0·61	—	—
		99·86		

The carbon dioxide in the analysis is that contained in the small amount of admixed spurrite, while the Al_2O_3, FeO, and MgO are probably represented in finely divided spinel. The analysis without further treatment is sufficient to show that the material here described is calcium orthosilicate.

Various calcium orthosilicates have been prepared experimentally in the laboratory. According to F. E. Wright[1] there are three distinct forms:

	Crystal-system.	Cleavage.	α.	β.	γ.	$\gamma - \alpha$.	Optic sign.
α-Ca_2SiO_4... ↓ 1420°	Monoclinic or triclinic	‖ prism axis	1·715	1·720	1·737	0·023	+
β-Ca_2SiO_4... ↓ 675°	Orthorhombic	‖ prism axis	1·717	—	1·735	0·018	+
γ-Ca_2SiO_4...	Monoclinic	‖ prism axis	1·642	1·645	1·654	0·015	−

α-Ca_2SiO_4 is much twinned, 2V is large, and the optic axial plane is nearly parallel to the prism axis, $\alpha' : c = 18°$.

β-Ca_2SiO_4 has 2V large and optic axial plane parallel to the prism axis.

γ-Ca_2SiO_4 has 2V 60°, optic axial plane perpendicular to the c-axis, extinction practically parallel to the cleavages.

The optical characters of γ-Ca_2SiO_4 are sufficiently distinctive, and if our larnite is to be correlated with any of these forms it must be with either the β or α form. The resemblance is closer to the α form, though the refraction of the β form is close to that of larnite. Referring to β-Ca_2SiO_4, Wright[2] says it 'appears in irregular rounded grains, often prismatic in shape with cleavage parallel to the prism axis. The crystal system is apparently orthorhombic, though the presence of twinning lamellæ with low extinction angles up to $c : \alpha' = 10°$ in certain of the grains which may be of the α form would indicate a still lower symmetry'. If β-Ca_2SiO_4 is truly orthorhombic, then the properties of our larnite are such as to suggest that it is α-Ca_2SiO_4.

The artificial α- and β-calcium orthosilicates are unstable minerals tending to pass over into the γ form at ordinary temperatures, and the inversion of β-Ca_2SiO_4, accompanied as it is by a large increase in volume (10% approximately), is known to be the cause of the dusting of cement. It is of interest, therefore, to determine whether any such signs of instability are indicated in the mineral larnite. It was noticed early in the examination of these rocks that certain of them

[1] A. L. Day, E. S. Shepherd, and F. E. Wright, Amer. Journ. Sci., 1906, ser. 4, vol. 22, p. 294.

[2] G. A. Rankin and F. E. Wright, Amer. Journ. Sci., 1915, ser. 4, vol. 39, p. 7.

were very difficult to prepare in thin section, the thin slice of rock breaking away suddenly into powder before the completion of the grinding. This was noted especially in rocks composed of the assemblage larnite-spurrite-spinel. That this powdering has nothing to do with the decomposition of the mineral in the presence of water

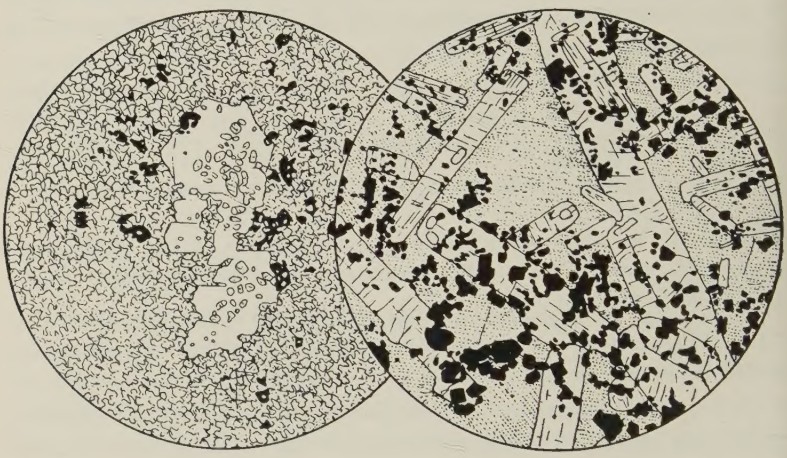


Fig. 2. Fig. 3.

Fig. 2. Larnite-spurrite-rock, showing a large porphyroblast of clear spurrite enclosing grains of larnite in a ground of granular larnite. ×21. (Sedgwick Museum Collection, Slice no. 26253.)

Fig. 3. Melilite (gehlenite)-merwinite-spinel-calcite-rock, showing sections of large tabular crystals of gehlenite and merwinite in a ground of calcite. The dark crystals are spinel, while perovskite is also present. ×21. (Slice no. 26036.)

is clearly indicated by the fact that dry specimens of the rock may be caused to powder or dust by the simple expedient of heating in a platinum dish to dull redness or even at lower temperatures. The powdering takes place when the rock fragment is allowed to cool, beginning at numerous points and gradually affecting the whole rock. Powdering may also be produced by shock. If a fragment be struck with a hammer and the surface then examined, it is seen that at the point of impact a thin skin of the rock after a short interval begins to swell and falls to powder. Shock then as well as heat may bring about dusting. The powder thus produced, when examined under the microscope, is seen to be constituted of the unchanged minerals spurrite and spinel, some unchanged larnite, and fibres of a mineral

with distinctly lower refraction ($\alpha > 1{\cdot}640$, $\gamma < 1{\cdot}660$), the position of the optic axial plane being perpendicular to the fibres and the optic sign negative. These features correspond with those determined for γ-Ca_2SiO_4. (The values of the refractive indices for the artificial γ-Ca_2SiO_4 (p. 81) will require amendment if the determination of the

Fig. 4. Fig. 5.

Fig. 4. Spurrite-larnite-rock, showing a large cleaved (and polysynthetically twinned) porphyroblast of spurrite enclosing grains of larnite and surrounded by a ground of larnite with dark spinel. ×21. (Slice no. 14888.)

Fig. 5. Spurrite-merwinite-rock, showing sections of large twinned and tabular crystals of merwinite in a ground of spurrite, both minerals enclosing numerous drop-like grains of larnite. ×21. (Slice no. 26262.)

optic sign as negative is correct, for then $\beta - \alpha$ should be greater than $\gamma - \beta$.)

It is noteworthy that the transformation is in some rocks remarkably sluggish. Even when powdering is produced by heat or shock, there may remain considerable amounts of unchanged larnite, the higher form being associated with the γ form, and residues of the former are sometimes found enclosed in a mantle of the latter. It is clear that a closer study of the transformation under controlled conditions is necessary, a study which may well go hand in hand with a closer examination of the artificial calcium orthosilicates.

(3) *Melilite-Gehlenite.*—A mineral of this group is sometimes an abundant constituent of these assemblages, especially those rich in spinel or merwinite. It occurs as idioblastic tabular (on 001) or

squarish crystals with a prominent basal cleavage and positive elongation (fig. 3). It is optically uniaxial and negative and never shows any anomalous birefringence. In these respects it resembles the much larger melilite crystals of the hybrid rock between the chalk and dolerite already described. Its refraction, however, is distinctly higher than that of the humboldtilite; ϵ is somewhat greater than 1·660, whereas ϵ of the humboldtilite is only 1·636. It is clear, therefore, that this melilite is richer in the gehlenite molecule, and the refraction is comparable with natural gehlenites, e. g. that of Velardeña, Mexico, which has ϵ 1·661. The natural gehlenites, however, still contain considerable percentages of the åkermanite molecule (Velardeña, 76% Ge, 18% Åk). We may therefore refer the melilite of the contact-zone of Scawt Hill to the gehlenite group.

(4) *Merwinite* ($3CaO.MgO.2SiO_2$).—This mineral, first described from the limestone contact-zone of Riverside, California,[1] in association with gehlenite, monticellite, and spurrite, is also a constituent of the Scawt Hill assemblages. Its association with spurrite is characteristic of the three occurrences from which it is now recorded. Its common associates at Scawt Hill are spurrite, melilite (gehlenite), and spinel. The optical properties agree closely with those determined for the mineral of the Riverside locality, and like larnite it stands out in relief from associated melilite or spurrite.

Its distinctive feature is its moderate double refraction and polysynthetic twinning. The mineral is optically positive, β 1·71, $\gamma - \alpha$ 0·012. The prominent cleavage is (010), γ standing perpendicular thereto. The polysynthetic twins are united along a prism plane (110) and twinning is on the *c*-axis. These lamellae form two sets at angles of 43° to one another, γ bisecting the obtuse angle between the lamellae. The orientation is $\gamma = b$, $a : c = 36°$. The crystals are tabular along (010), and they may reach in length up to 3 mm., though usually much smaller (fig. 5).

(5) *Spinel.*—Some of the contact-rocks are black in colour due to the abundance of finely-divided spinel. In these spinel-rich rocks, calcite, spurrite, melilite (gehlenite), or merwinite are the common associated minerals. In thin sections they are seen to be rich in well-developed octahedra of spinel of a deep-brown or greenish-brown colour and optically isotropic.

Material in a pure condition is easily separated from the rock by treatment with hydrochloric acid, whereby calcite and the silicates

[1] E. S. Larsen and W. F. Foshag, Amer. Min., 1921, vol. 6, p. 143.

are completely removed. The spinel thus purified has been analysed by W. H. Herdsman with the following result (I):

	I.	II.	Molecular ratios.		Molecular composition.	%
Al_2O_3 ...	57·30	57·30	5617	6349	$FeO.Fe_2O_3$ ...	17·0
Fe_2O_3 ...	25·50	11·71	732		$FeO.Al_2O_3$ ...	17·26
FeO ...	—	12·41	1724	6349	$MgO.Al_2O_3$ ...	65·67
MgO ...	18·50	18·50	4625			
	101·30	99·92				

In I all the iron is estimated as Fe_2O_3. A separate estimation of FeO gave a value of 10·40%, but owing to the great difficulty experienced in bringing the mineral into solution this estimate is low, as a small residue was left. In column II the analysis is restated with the 25·50% Fe_2O_3 adjusted in accordance with an $RO : R_2O_3$ formula. As thus computed the spinel is seen to be a pleonaste with significant percentages of the magnetite molecule.

Discussion.—Spurrite, larnite, melilite (gehlenite), merwinite, and spinel are thus the chief minerals of the Scawt Hill contact-zone. This enumeration does not exhaust the list of minerals found with these assemblages. There are secondary minerals produced by the decay of some of these primary constituents, but they have not yet been studied in any detail and any account of them must be deferred. Monticellite, though carefully sought for, has not been identified among the assemblages.

Wollastonite is not a normal constituent of the contact-zone, but it occurs rather plentifully in parts of the hybrid zone. There is, however, one type of occurrence of wollastonite which is of interest. It is developed at the immediate contact of flint nodules in the chalk. In the contact-zone small flint nodules have been observed occurring in a larnite-rich rock. At the immediate contact with the nodule the larnite gives place to wollastonite, which forms a sheath between the larnite and the microcrystalline quartz of the nodule, a clear indication that calcium orthosilicate is unstable in the presence of free silica at the temperature of metamorphism.

Among these minerals, merwinite is not recorded from dry melts, but is there represented by mixtures of monticellite and calcium orthosilicate. An orthorhombic spurrite (α-spurrite) has been produced by Shepherd[1] and by Eitel[2]; the former by heating $CaCO_3$ and Ca_2SiO_4 with 10% NaCl solutions at temperatures of 350–400°,

[1] F. E. Wright, Amer. Journ. Sci., 1908, ser. 4, vol. 26, p. 551.

[2] W. Eitel, Neues Jahrb. Min., 1923, vol. 48, p. 63.

the latter from a melt at 120 atmospheres CO_2 pressure. According to Eitel, α-spurrite melts incongruently with separation of β-Ca_2SiO_4 at 1380°, while natural spurrite heated under pressure inverts to the orthorhombic synthetic form at 1200°. The reverse transformation has not been effected, and α-spurrite would appear to be the stable form of this compound.

It is clear that this contact-zone has suffered considerable metasomatic effects. The purity of the chalk outside the thermal zone clearly denotes that solutions from the dolerite magma enriched the contact-zone in silica, magnesia, iron oxides, and alumina, so enabling the formation not only of the calcium silicates, but also of merwinite, melilite (gehlenite), and spinel.

Many of these assemblages in normal aureoles would be represented by rocks composed of diopside-wollastonite-grossular-calcite. The unusual character of the Scawt Hill assemblages is probably connected with the high temperature prevailing during metamorphism. In this process, the solutions emanating from the magma played a necessary part, modifying the composition and effecting a rapid rise in temperature in the limestone apart from conduction. It seems not improbable that such unusual assemblages are likely to be preserved for observation where the rise and fall of temperature has been comparatively rapid, reactions among the minerals formed at high temperature being inhibited by rapid cooling. If this be so such assemblages are not unexpected in contact-zones of small intrusions.

Acknowledgements.—The writer is greatly indebted to Dr. Harker for his kindness in executing the drawings of fig. 2–5, which accompany the text, and to Mr. R. Bell, of Belfast, who has kindly forwarded specimens and conducted the writer to this interesting locality.

'Bauxite' from Kashmir.

By T. V. M. Rao, Ph.D. (London), D.I.C.
Research student, Imperial College of Science and Technology, London.

[Communicated by Prof. W. W. Watts, F.R.S.; read March 20, 1928.]

ALTHOUGH frequent references have been made during recent years to the 'bauxite' deposit of Jammu in Kashmir, no complete account giving its geological relations is yet available.[1] The only published account is that of Middlemiss,[2] and Fox[3] has also made brief references to it in his recent book on bauxite. Previous work on bauxite by the present writer[4] induced him to examine these rocks, and through the kind intervention of Prof. W. W. Watts a complete set of them was obtained from the authorities in Kashmir. Only the petrological and chemical aspects of these specimens have been dealt with here, and consideration of any possibility of their economic use has been avoided.

Field relations.—The deposit is said to form a bed from 7 to 10 feet thick overlying the 'Great Limestone' of 'unknown age but probably older than Trias', and it is separated from this by a thin zone of siliceous breccia. Laterally it passes into a bed of clay, and it is generally overlain by the Sabathu coal beds, with which it is also laterally continuous in one locality. The coal beds are Eocene in age. From certain points of similarity to the French bauxite and with the evidence obtained in the field during the recent work of the Geological Survey of India, Middlemiss has been able to deduce an age between Gault and Eocene for this deposit. It is stated that the area, where this deposit occurs, has been elevated into a set of elliptical domes breaking through the Siwaliks of the sub-Himalayan zone with

[1] Since writing this paper a report by C. S. Middlemiss on this deposit has been published by the Mineral Survey Department of the Jammu and Kashmir Government. [Min. Abstr., vol. 4, p. 78.]

[2] C. S. Middlemiss, Presidential Address, 9th Indian Sci. Congress, Proc. Asiatic Soc. Bengal, 1922, n. ser., vol. 18.

[3] C. S. Fox, Bauxite, London, 1927, pp. 33–4, 89, 127–8, and 141–2.

[4] T. V. M. Rao, A study of bauxite. Min. Mag., 1928, vol. 21, pp. 407–30.

the ' Great Limestone ' forming their core. Further, according to Fox, the area has suffered great tectonic disturbance.

Megascopic characters.—In hand-specimens these rocks are mostly massive, though spherulitic types are not uncommon. The spherules are closely cemented by the matrix and present a crushed appearance. The rocks are hard and scratch glass easily. Many of them show a bedded structure, probably reminiscent of the rocks from which they are derived, and a few have developed a distinct cleavage in one direction due to metamorphism. The colour varies from cream-white to grey, the latter owing to the presence of organic impurities. The average specific gravity is 3·2.

Microscopic characters.—Thin sections of these specimens are opaque and have to be examined by reflected light. The texture is compact except for the presence of a few empty holes. But many sections show distinct traces, such as of bedding planes, suggesting their probable origin from beds of clay. The spherules, the structure of which is seen to greater advantage in thin sections, have lost their rounded shape and have become elongated. Embedded in the opaque material can often be seen clusters of minute crystals of diaspore showing the characteristic high birefringence and bright polarization-colours.

But an examination of the grains obtained by crushing the rock reveals several important features. There are numerous grains of opaque aluminous material, and along the edges of some of them are found attached minute crystals of diaspore. In a few cases these opaque grains are slightly stained with iron, which, besides being present in this form, occurs also as grains of haematite and limonite. Ilmenite and anatase, the latter as deep-blue and brown grains, are the forms in which titanium occurs in these rocks. An appreciable amount of gibbsite and an occasional waterworn grain of brown tourmaline are not of uncommon occurrence.

Chemical characters.—From a chemical standpoint also these rocks are not without interest. All the specimens examined are found to be highly refractory, and special treatment[1] is invariably necessary to reduce them to a state fit for carrying out chemical analysis, a complete report of which is given below. Microscopic examination of the unattacked part of the residue obtained after the first fusion with sodium carbonate proved that diaspore was the refractory

[1] Prolonged heating with potassium bisulphate or repeated fusion with sodium carbonate is necessary to get all the diaspore present into solution for carrying out the analyses.

material present in the rock, and this was further confirmed by a similar treatment of a fresh specimen of that mineral obtained from the Imperial College collection. Owing to the indefinite amount of diaspore present, the refractory nature varied in its extent in the different specimens.

Chemical analyses of typical specimens from the Jammu deposit.

	Pisolite West of Jangal.	Chakar, C.d. 3rd foot.	Chakar, C.s. 1st foot.	Chakar, C.v. 1st foot.	Chakar, D.c. 2nd foot.	Chakar, D.e.[1] 3rd foot.
SiO_2 ...	0·84	6·78	6·53	14·07	0·79	1·31
Fe_2O_3 ...	1·09	3·56	1·68	3·88	0·75	1·86
Al_2O_3 ...	78·34	70·71	73·43	61·70	80·74	78·24
MgO ...	0·13	0·05	0·02	0·03	0·77	0·04
CaO ...	0·20	0·02	0·10	0·22	0·10	0·21
K_2O ...	nil	nil	0·24	nil	n.d.	0·15
Na_2O ...	nil	nil	0·42	0·56	n.d.	nil
H_2O+ ...	14·99	14·37	13·87	14·48	12·15	14·59
H_2O- ...	0·03	0·71	0·21	0·39	0·11	0·13
TiO_2 ...	4·35	4·36	3·08	3·90	3·38	2·48
C ...	0·22	0·12	0·11	0·82	1·46	1·35
	100·19	100·68	99·69	100·05	100·25	100·36

It will be noticed that the alumina content is very high in these specimens and in a few cases the silica is also considerable. The rather low water content needs special mention. Alkalis, magnesia, and calcium oxide, whenever present, are only in very small amounts. Carbon is an invariable constituent and in some cases its amount is appreciable. Although special search was made, the carbon was found to occur in no form other than as an organic impurity imparting a dark grey colour to the specimens. The associated coal-bearing beds may possibly account for the presence of this element in the rock.

Mineral composition.—Excluding the minor constituents, the percentage of alumina and water present in these specimens is approximately 85 and 15 respectively, thus corresponding to a monohydrate in composition. The amount of diaspore present in them is too insignificant to give this composition to all the alumina, and consequently the opaque material forming the bulk of the rock should also bear a composition corresponding to a monohydrate, resembling the earthy mineral occurring in France and described by Böhm.[2]

[1] These letters below the localities of the specimens refer to the trial pits, the positions of which are marked on the maps in the Mineral Survey Report.

[2] J. Böhm, Zeits. Anorg. Chem., 1925, vol. 149, p. 203. [Min. Abstr., vol. 3, p. 430.]

There seems to be a strong tendency in commercial circles to designate all rocks and minerals used in the extraction of aluminium and the preparation of its salts as 'bauxite'. For reasons given elsewhere [1] a restricted use of the term has been attempted, and in accordance with that the Kashmir material will have to be included among the monohydrates. The monohydrate occurring in France, since called boehmite by J. de Lapparent,[2] has been found on examination to give a characteristic X-ray spectrum [3] suggesting that it is a definite mineral distinct from diaspore. Although it has not been possible to carry out a similar X-ray examination with the Kashmir specimens, so far as can be made out from their chemical and physical properties the opaque monohydrate present in them corresponds to the boehmite occurring in France.

The process of formation of the aluminium-bearing rocks occurring in Jammu, Kashmir, may be described summarily as follows. The bed of clay overlying the limestone was lateritized, giving rise to bauxite. Through some process not yet clear, the bauxite, as has happened in France, was partly dehydrated, giving rise to boehmite. The alteration of part of this mineral into diaspore was probably brought about through thermodynamic metamorphism during the tectonic disturbances of the Himalayan uplift. So it is evident that this deposit in Kashmir is really composed of a mixture of a small amount of diaspore and abundant boehmite with a few accessory minerals.

Professor C. G. Cullis has informed the writer of what may be a similar case in Naxos, Greece. A blanket of laterite appears to have been dehydrated and converted by metamorphism into emery, the latter carrying a certain proportion of diaspore which is presumed to represent the bauxitic material of the laterite only partly dehydrated. That the area has suffered infra-plutonic metamorphism is suggested by the occurrence at no great distance from the emery deposits of a granite batholith and by the alteration of sedimentary limestones and shales associated with the emery deposits into marble and mica-schists respectively. The Jammu deposits have probably undergone alteration on parallel lines, though not so intensively as at Naxos.

[1] T. V. M. Rao, loc. cit., p. 425.

[2] J. de Lapparent, Comp. Rend. Acad. Sci. Paris, 1927, vol. 184, p. 1661. [Min. Abstr., vol. 3, p. 369.]

[3] W. F. de Jong, Zeits. Krist., 1927, vol. 66, p. 303. [Min. Abstr., vol. 3, p. 430.]

Highly siliceous beds, formed by the accumulation of the silica leached out during lateritization, are of common occurrence below deposits of laterites (vide Fox, loc. cit., p. 30). On the other hand, Middlemiss definitely considers from field evidence that the siliceous breccia beds underlying the boehmite deposits of Jammu are not genetically related to them, but form part of the 'Great Limestone'.

In conclusion, the writer wishes to record his indebtedness to Prof. W. W. Watts for facilities afforded for carrying out this work and also for kindly reading the manuscript of this paper. He is grateful to Dr. H. F. Harwood for helpful suggestions and supervision of the chemical analyses. Thankful acknowledgement is to be made to Mr. C. S. Middlemiss and to the Foreign and Commerce Minister of Kashmir for providing the material and also for granting the necessary permission to make use of it.

Inclusions in the apatites of some igneous rocks.

By A. W. Groves, M.Sc., Ph.D., D.I.C.
Assistant Petrologist and Chemist, Geological Survey of Uganda,
and A. E. Mourant, B.A.

[Communicated by Prof. W. W. Watts, F.R.S.; read March 19, 1929.]

In a recent paper by Dr. W. F. Fleet and Dr. F. Smithson[1] attention was drawn to the occurrence of dark apatites and apatites with dark cores of inclusions in certain sediments of the Midlands of England, and it was pointed out that the only other definite occurrences known of these peculiar apatite grains in either igneous or sedimentary rocks appeared to be restricted to the Old Red Sandstone of the Cardiff area,[2] the 'newer' granites of Jersey,[3] and the Leinster granite.[4] These writers also expressed the hope 'that any future observation of such grains may be recorded with a view to tracing the source of the detrital grains of Welsh and English rocks'. Dr. W. Mackie has since recorded[5] dark cores in the apatite of the 'Benrinnes grey granite (Ruthrie), in some of the apatites of Loch Moy granite, Ross of Mull, Noesting (Shetland), some of the central Grampian rocks and all or nearly all the Galloway granites'. The object of these notes is to record further occurrences of dark apatite and apatites with dark cores, at the same time making some observations on the nature of the inclusions.

Part I. Apatite in the granites of Normandy, Brittany, and Jersey (by A. W. Groves).

Barfleur granite, Normandy.—The inclusions form a solid rod-like core with sharply defined straight margins running down the centre of the crystal parallel to the prism faces. The core usually terminates

[1] W. F. Fleet and F. Smithson, Geol. Mag. London, 1928, vol. 65, pp. 6–8.

[2] A. Heard and R. Davies, Quart. Journ. Geol. Soc. London, 1924, vol. 80, p. 501.

[3] A. W. Groves, Geol. Mag. London, 1927, vol. 64, pp. 244, 249.

[4] W. J. Sollas, Trans. Roy. Irish Acad., 1891, vol. 29, pp. 434–5; F. Smithson, Geol. Mag. London, 1928, vol. 65, pp. 14, 19.

[5] W. Mackie, Trans. Edinburgh Geol. Soc., 1928, vol. 12, p. 28.

with rounded or frayed ends before reaching the end of the crystal, and the length of the core is very variable. Some of the cores are practically opaque while others transmit light and show marked absorption parallel to their length, the colour range being from greenish-grey to nearly black. The majority of the apatite grains in the specimens examined from this granite mass contained dark central cores. Some rare cases have been observed where the core shows crystalline outline corresponding to that of the enclosing apatite crystal; basal sections of apatite have in several instances shown six-sided cores. One case has been noted from Port de Landemer in which an apatite crystal consisted of a black almost opaque core, surrounded by a sharply defined zone of grey apatite, and this in turn surrounded by clear apatite. The grey zone clearly displayed the same crystal forms as the external ones, while the opaque zone at the centre also showed the same forms.

Flamanville granite, Normandy.—Occasional inclusions of a greenish-brown colour and others almost opaque occur, but cores are much less common than in the Barfleur granite.

Jersey.—The presence of apatite with dark central rod-like inclusions in the 'newer' granites of Jersey has already been recorded by the writer (loc. cit.). With low magnification the cores appear almost opaque. Using a magnification of 500 diameters and a strong light, the central cores are seen to be generally of greenish-brown or greenish-grey tint. Sometimes there is a marked absorption of light parallel to the length of the core. In a few favourable cases it has been noted that the core has a fairly high birefringence and has positive sign of elongation like those recorded by Smithson from the Leinster granite, but none of the purple shades occurring in the Leinster granite are found in Jersey.

A weathered granite pebble, extracted from the Rozel conglomerate of the north-east of Jersey, when crushed yielded a suite of heavy minerals among which apatite crystals with central cores of opaque foreign matter were common. Other types of granite pebbles in this conglomerate do not yield apatite with cores.

Chausey Islands, Normandy.—Apatite grains with central cores of inclusions of variable character are common in two specimens of granite from these islands.

Brittany.—The belt of porphyritic pink granites, designated by the French Geological Survey as 'granite porphyroïde de l'Aber Ildut', running from Trégastel through Pleumeur, Carantec, St. Pol de Léon,

l'Aber Ildut, and Île Melon (near Brest), is throughout characterized by abundant apatite containing cores of many types. The following main types are to be distinguished:

(*a*) Nearly opaque rod-like masses. (Figs. 5 and 6.)

(*b*) A central zone, sometimes rather ill-defined, pleochroic from light-grey to greenish-grey or brown and suggestive of finely dispersed chlorite or green biotite. (Fig 3.)

(*c*) A central strip, generally of rectangular shape, consisting of what appears under moderate magnification to be a zone of transverse fibres. Under high magnification the 'fibres' are seen to be segregations of dark foreign matter along parting planes parallel to the basal plane. This type generally shows little pleochroism.

(*d*) A rectangular or irregular strip pleochroic from grey to a bluish or purplish tint and having the same other optical properties as the rest of the crystal. Central voids often occur in the grey area. (Fig. 2.)

(*e*) Another type of core is frequently observed consisting of the characters of types (*c*) and (*d*). The pleochroism of this type is generally marked. (Fig. 1.)

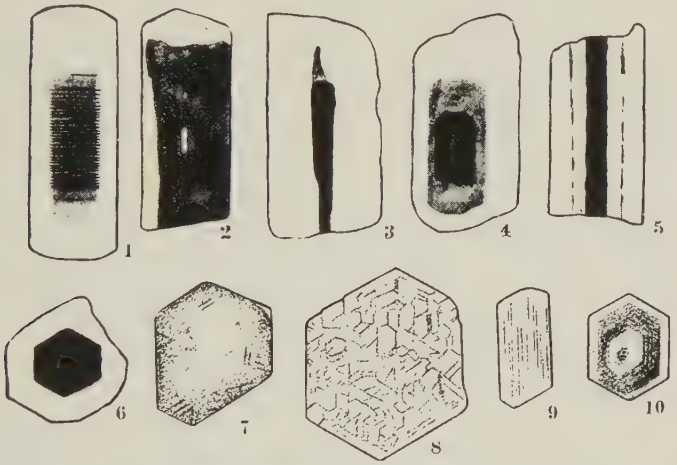
In all cases where pleochroism is visible the absorption for ϵ is greater than for ω.

Gault Clay.—A sample of Gault Clay from about two miles east of Dorking, Surrey, yielded large grains of apatite two of which contained finely developed central cores of deep greenish-brown. The cores are non-pleochroic, sharply defined, and measure 0·1 mm. in width.

Thanet Sand.—A single grain of apatite with a central core of non-pleochroic opaque matter has been noted from the Thanet Sand of Ewell, Surrey.

General Remarks.—Attempts to determine the nature of the inclusions in the examples just described have yielded little evidence in grains of types (*a*), (*c*), (*d*), and (*e*). Despite the different colours, the writer is of the opinion that the nature of the inclusions in most of the types other than type (*b*) are similar, and that the different degrees and ranges of pleochroism produced are dependent on the size and arrangement of the fine particles of foreign matter. Those of type (*b*) which show a greenish-brown colour, maximum absorption parallel to length, strong birefringence, and positive sign of elongation are suggestive of biotite, but the number of grains showing all these characters is relatively small. In other cases in type (*b*) the greenish-

brown colour is accompanied by no indications of birefringence, and chlorite is suggested as a probability. One broken grain has been noted in which a core of type (*b*) protruded through the end owing to fracturing away of the surrounding apatite. The core was green, fairly broad and flattened, and could be definitely identified as



FIGS. 1–10. Apatite crystals with inclusions, from: 1, Trégastel, Brittany; 2, St. Pol de Léon, Brittany; 3, Flamanville; 4, Port de Landemer, near Barfleur; 5, La Pulente, Jersey; 6, St. Pol de Léon; 7, Surville Manor, Jersey; 8 and 9, Bonne Nuit Bay, Jersey; 10, Pors-Even, north Brittany. Figs. 6, 7, 8, and 10 are of transverse sections, the others longitudinal. Magnification: Figs. 1–6 ×100, 7–10 ×200.

green biotite. In yet other cases the core consists of opaque discrete particles, and quite commonly is a rod of opaque matter (type (*a*)). A few apatite grains have been noted with a central void or gas inclusion in place of a core. Sometimes the central void is partly filled with opaque particles of foreign matter.

For the zoning of the Dartmoor zircons Dr. A. Brammall has suggested the following as a possible mechanism. The growth of a crystal of X from its solution creates a two-way migration of molecules: (1) An inward diffusion of the constituents of X towards the centre of crystallization; and (2) An outward diffusion and repulsion of substances not required by X. Alien substances thus repelled tend to become temporarily concentrated in a very narrow fluid zone around the margin of the crystal X, and for one of

these substances, say Y, the concentration may reach the labile state with the result that a cloud of crystalline Y particles may suddenly arise. As the precipitation of Y particles would automatically raise the concentration of X in the zone of precipitation, growth of X, suddenly accelerated, might overstep the Y particles and enclose them in a definite growth zone. This process, repeated rhythmically, would explain the zoning of the Dartmoor zircons by ilmenite dust.

Such a theory would explain the presence of biotite and chlorite as inclusions in apatite—minerals which generally crystallize after apatite. The cores of inclusions could then be explained as apatite charged with inclusions forming the dark core, a sudden change of physical conditions causing the rest of the crystal growth to be clear and devoid of inclusions. The grey areas described may be due to zoning on a sub-microscopic scale, the reflection and transmission of light from such small particles giving rise to colour effects simulating pleochroism. A zoned crystal such as that of fig. 4 would represent two well-defined changes in the physical conditions; fig. 10 is a comparable case to that of the zoned zircons; while in fig. 5 the outer thin zone of inclusions would indicate a temporary return to conditions favourable for the formation of inclusions.

The regular arrangement of inclusions in chiastolite is known to be due to the fact that the particles consisting of carbon in the solid state exert no osmotic pressure and are consequently passive to the forces exerted by the growth of the crystal. The plates of foreign matter parallel to the basal plane in the cores of types (*c*) and (*e*) (fig. 1) seem to be more readily explained by some such theory as that generally held for chiastolite. The same remark also applies to crystals of the type of fig. 8.

There are numerous references in text-books[1] to apatite crystals with inclusions and showing pleochroism. In all the cases of pleochroic apatite examined by the writer the pleochroism is seen under high magnification to be confined to the core of inclusions; with magnifications of less than about 50 diameters the whole grain often has the appearance of being pleochroic.

I wish to thank Prof. W. W. Watts and Dr. A. Brammall for critically reading the manuscript of these notes.

[1] J. P. Iddings, Rock Minerals, 2nd edit., 1911, p. 524; E. Weinschenk, Petrographic Methods, New York, 1912, p. 237; F. H. Hatch and A. K. Wells, Text-book of Petrology, 1926, vol. 1, pp. 114–15.

Part II. Apatite in the volcanic rocks of Jersey and Brittany (by A. E. Mourant).

A study of the volcanic rocks, presumed to be pre-Cambrian, of Jersey and north Brittany has brought to light a number of instances of apatite with inclusions and apparently pleochroic.

Jersey.—The Jersey examples all occur in andesites, and the apatites of nearly all the normal andesites show at least traces of inclusions. All the andesites examined, however, from the contact-metamorphic aureole of the 'newer' granite show apatites entirely free from the characteristic inclusions, though they are of the same size and shape as those in the unaltered andesite.

Longitudinal sections show innumerable dark fibres arranged in lines parallel to the length of the crystal. The larger fibres show visible pleochroism, being practically opaque to light vibrating parallel to their length, and dark brown for the perpendicular vibration. The fibres occasionally show visible double refraction which must therefore be very high. In one case it appears that they have positive elongation. Elongated cavities can be detected in addition to normal fibres in a few crystals. A few large negative crystals contain irregularly arranged partly chloritized biotite.

In transverse sections the crystals show the inclusions in lines about one inclusion deep, forming an irregular network approximating, in some cases very closely, to a lattice-work of lines parallel to the traces of the prism faces. The lines seldom, if ever, cross one another.

Oblique and longitudinal sections show that the pattern is remarkably constant from end to end of the crystal. The terminations of the crystals are frequently irregular as though broken. In such cases the inclusions run unaffected to the end. Where pyramid faces are present a short, ill-defined terminal zone is generally clear. Inclusions are occasionally crowded (generally individually parallel to the prism edges) along surfaces parallel to the basal planes and along irregular surfaces resembling cracks.

The lattice structure is best seen in the apatite of andesite from the top of the slope south of the west end of Bonne Nuit Bay (figs. 8 and 9). At Surville Manor the chief characteristic is a marked crowding of the inclusions towards the crystal margins (fig. 7).

Two somewhat unusual types of apatite occur with others in a section of much weathered andesite, probably ash, from near Highfield, St. Saviour. One type contains numbers of opaque plates

parallel to the basal plane of the crystal. Only two such crystals are present, and it is impossible to determine the optical characters or the finer details of structure. This type is perhaps the same as type (*c*) above and, like it, shows no pleochroism. The other variety in the same micro-section is also represented solely by two crystals. These are colourless for the ordinary ray and quite uniformly pale reddish-brown for the extraordinary. Both crystals occur in very rusty parts of the slide and there is a strong suggestion that the colour is due to iron introduced during weathering. This is the only case in which the apatite itself definitely appears coloured.

Brittany.—In north Brittany the inclusions are apparently of the same nature as that common in Jersey but are sometimes sub-microscopic. As the fibres get smaller and smaller the host takes on an appearance of pleochroism and colour change becomes more conspicuous, with ϵ pure dark grey and ω pale brown, as would be expected from the comminution of the larger fibres. This effect is hardly seen in the Jersey examples. Another marked difference is in the arrangement of the fibres in zones parallel to the crystal faces. The longitudinal arrangement is unchanged.

At Pors-Even in a somewhat basic variety of the 'porphyre pétro-siliceux' the apatites generally show traces of a core of rather coarse inclusions followed by finer matter collected in, but not entirely confined to, very sharp zones of growth of which nine were counted in one crystal (fig. 10). A flow-breccia of similar composition at Les Heaux contains many small apatites with pleochroic cores in which many of the inclusions are sub-microscopic. A few crystals have larger inclusions more widely distributed and showing definite traces of the lattice arrangement.

North of Pors-Even, in the 'orthophyre de Tréguier' most of the apatites are water-clear, but a few show strong pleochroism, while inclusions are only indistinctly seen with the highest power. One or two dark zones are visible with traces of a much finer zoning. The external layer is always clear.

The 'albitophyre de Pors-Hir' at L'Arcouest contains apatites with inclusions confined to a relatively small core, probably with a clear centre. The inclusions are mostly sub-microscopic. The depth of darkening is moderate. One example shows a rather indefinite central core in which separate inclusions are just visible. This is separated by a clear zone from a sheath showing crystal outline in which separate bodies cannot be seen. The exterior of the crystal is clear.

The apatites of this rock as a whole greatly resemble those described above from the granite.

The nature of the inclusions is probably identical in all the examples described from the volcanic and hypabyssal rocks of Jersey and north Brittany, but they are best examined in those of Jersey. Haematite and manganite are suggested as possibilities. The absence of signs of a platy habit and of pleochroism in transverse sections is, however, against the former, while the pleochroism is almost too strong for the latter.

I wish to thank Prof. W. J. Sollas for his helpful criticism during the preparation of this paper.

A contribution to the petrology of the Whin Sill.

(With Plates III and IV).

By S. I. Tomkeieff, F.G.S.

Armstrong College, University of Durham, Newcastle-upon-Tyne.

[Read June 12, 1928.]

Contents.

I. Introduction 100
II. Petrographical description... 100
(1) Fine-grained variety ... 101
(2) Medium-grained variety 101
(3) Coarse-grained variety 102
(*a*) Field occurrences 103
(*b*) Petrography ... 104
III. Certain exceptional varieties of the Whin Sill ... 109
(1) Red acid segregations... 109
(2) Spheroidal aplitic inclusions 111
(3) Pectolite inclusions ... 112
IV. The specific gravity... ... 113
V. On the genesis of the coarse-grained variety of the Whin Sill and acid segregations, and its bearing on the question of magmatic differentiation 114

I. Introduction.

THE 'Whin Sill' of the north of England is a classic example of an igneous intrusive sheet. A detailed account of its general tectonic and petrographic features has been the subject of a recent paper by A. Holmes and H. F. Harwood.[1] The present author has made the attempt not so much to give a complete account of the petrology of the Whin Sill, as to describe certain peculiar developments within its mass, such as the coarse-grained bands, acid segregations, &c.

II. Petrographical Description.

Although remarkably uniform in its petrographical characters and its chemical composition, the rock forming the sill can be subdivided into three main types or varieties:

(1) Fine-grained variety (basaltic type), occurring along the upper and lower contacts (cooling selvages). It passes rapidly into the

(2) Medium-grained variety (doleritic type), which is the normal and dominant type.

[1] A. Holmes and H. F. Harwood, The age and composition of the Whin Sill and the related dikes of the north of England. Min. Mag., 1928, vol. 21, pp. 493–542.

(3) Coarse-grained variety (gabbroid type) is of a remarkably coarse texture, occurring in the form of bands, segregation veins, and spheroids, always sharply separated from the normal rock. This variety is of comparatively rare occurrence and forms an extremely small proportion of the rock.

(1) *Fine-grained variety.*

The fine-grained variety (selvage) is produced by the rapid cooling of the intruded magma at the contact with the sedimentary rocks. It varies in texture from anchi-tachylytic to aphanitic. Numerous felspathic microlites together with a few augitic grains are embedded in a brownish semihyaline groundmass. Sometimes microphenocrysts of augite are present. Iron-ore is present in the form of fine skeletal grid-like aggregates of early crystallization and also in the form of small granules, sometimes moulded on felspar and augite. Occasionally we may observe small phenocrysts entirely transformed into an aggregate of serpentine and iron-ore, which suggests a former presence of olivine. These small and isolated phenocrysts may therefore be relics of an early crop of olivine, subsequently resorbed or partly autopneumatolized by the magma.

In certain places in the fine-grained, as well as in the medium-grained, variety small amygdules are found. They are usually composed of calcite, quartz, and chlorite. Often small spongy pyritic spheroids are found at the contact (usually at the contact with shales). In contact with limestone or marly shale a certain amount of assimilation is observed in the form of light coloured selvage bands with a marked flow-structure.

(2) *Medium-grained variety.*

As this variety has been already described by Prof. Holmes, only a few additional observations will be presented here. A series of representative micro-sections taken along the whole outcrop of the Whin Sill was measured by means of Shand's micrometric stage under a 1-inch objective. The results of these measurements brought up to 100 % are presented in Table I. At first sight these results are not comparable with those of Holmes, but in this connexion we must point out that Holmes definitely excluded from his measurement of felspar, not only the decomposition products (sericite, &c.), but also the leucocratic mesostasis, which is included in our case with the felspar, while the melanocratic mesostasis was measured together

with the melanocritic constituents (hornblende, biotite, chlorite). The fluctuation in the amounts of minerals in different specimens is to be explained, not so much by the actual variation of the rock, as by the effect of sampling.

Table I.—Mineralogical composition of the medium-grained variety of the Whin Sill (percentages by volume).

	Felspar.	Pyroxene.	Hornblende and chloritic mesostasis.	Iron-ore.	Iron-pyrites.
Crook boring	56·06	35·40	1·51	6·85	0·18
High Force (quarry) ...	57·21	30·70	7·67	4·42	—
High Force (waterfall)	61·00	30·55	2·44	5·77	0·24
Little Whin Sill, Weardale	56·18	33·50	2·25	8·07	—
Greenhead quarry ...	58·30	31·30	3·92	6·48	—
Craig Lough	63·60	30·93	—	5·47	—
Belford...	58·38	27·13	9·20	5·29	—
Little Mill	52·04	26·65	12·80	8·51	—
Average (volume) ...	57·72	30·87	5·05	6·36	
,, (weight) ...	51·28	34·05	4·55	10·12	

There is but little to add to Holmes's description of the constituent minerals. The monoclinic pyroxene was found to be the predominating ferromagnesian constituent, but in some cases (lower part of the sill at Craig Lough) large phenocrysts of the orthorhombic variety were observed. Some of these phenocrysts enclose small felspar laths and also minute crystals of normal monoclinic augite. They also show a marked effect of resorption and are moulded on by the normal pyroxene of the groundmass. This, together with the observed fact that in the fine-grained marginal facies one can sometimes observe microphenocrysts of augite, does not entirely tally with the proposed normal sequence of crystallization (see p. 108). A light-coloured enstatite-augite variety of pyroxene is found sporadically distributed through the Whin Sill. This evidently belongs to an early period of crystallization, and it is greatly autopneumatolized.

(3) *Coarse-grained variety* (*Dolerite-pegmatite*).

Already in 1824, Adam Sedgwick, who had made a thorough survey of the Whin Sill of Teesdale, had noticed the coarse-grained variety, and J. J. H. Teall[1] was the first to give a petrological description of this variety.

[1] J. J. H. Teall, On the chemical and microscopical characters of the Whin Sill. Quart. Journ. Geol. Soc. London, 1884, vol. 40, p. 640.

(*a*) *Field occurrences.*—The coarse-grained variety can be observed in nearly all outcrops of the Whin Sill where the sill attains a considerable thickness in the region of the South Tyne and Tees basins. With the exception of Caw Burn, no coarse whin was ever found north of the Tyne, and it is also absent in the thinner portions of the sill in the outcrops along the Pennine escarpment and in Lune Dale.

The coarse-grained variety is invariably restricted to the upper half of the sill, and occurs in the form of flat bands. The bands are more of the nature of flattened lenticular masses enclosed in the sill, parallel to its intrusive margins, and often show a rapid thinning out accompanied by bifurcation or branching. Very often the bands exhibit a wavy outline, a kind of flow-structure on a large scale being shown by the band as a whole, but not by its constituent minerals among which the fluxion texture is entirely absent. In thickness the bands vary from a fraction of an inch to six feet. The boundary line between the coarse- and the medium-grained rock is always sharp and well defined, but the transition from one variety to the other, as seen in the micro-section, is perfectly continuous.

The coarse-grained variety has been observed in the following localities:

Crook boring, Co. Durham. At Roddymoor colliery, near Crook, a deep boring revealed the presence of the Whin Sill (187 ft. 1 in. in thickness) intruded in the Scar Limestone. Dr. Woolacott,[1] who gave an account of this boring, found the coarse-grained band (4 or 5 ft. in thickness) to occur near the middle of the sill. The rock is remarkably coarse, and some of the pyroxene crystals are over 1 in. in length.

Middleton in Teesdale. Bands of the coarse rock occur in the upper part of the sill, and can be observed in the two quarries south of the river Tees and also near the Whinch Bridge.

High Force, Teesdale. There is a good exposure of several bands in the quarry just above the hotel. Altogether four bands were to be seen in the quarry face in 1927. They were all parallel to the plane of intrusion, thinning out in a westerly direction. Their respective maximum thicknesses were as follows: 2, ½, 6, 6 inches.

Cronkley Fell, Maize Beck, Langdon Beck, and Caldron Snout. At all these localities in Teesdale coarse bands are to be found in the

[1] D. Woolacott, A boring at Roddymoor colliery, near Crook, Co. Durham. Geol. Mag. London, 1923, vol. 60, p. 50.

upper part of the sill. Above the waterfall at Caldron Snout, near the new bridge, there are fresh exposures of a very thick (up to 6 ft.) band which ramifies into a series of undulating veinlets.

Tyne Head, Cumberland. A band 8 in. thick, rapidly thinning out in a westerly direction, is exposed at the foot of the waterfall.

Gilderdale Burn, near Alston, Cumberland. A band 6 to 8 in. in thickness is exposed on the south bank opposite the rapids. This rock is very interesting as it shows pink segregation patches.

Lambley Burn and Black Burn, south-west of Haltwhistle, Northumberland. Coarse bands are found in Lambley and Tindale quarries and also near the waterfall in Black Burn.

Caw Burn, near Haltwhistle, Northumberland. The coarse-grained rock occurs in the form of spheroids, often enclosing fibrous pectolite.

(*b*) *Petrography.*—Megascopically the rock is very coarse and gabbroidal, with conspicuous long blades of lustrous black pyroxene (up to 2 in. in length), often curved and twisted, resembling blades of grass. Frequently the pyroxene blades form clusters radiating inwards into the band. The felspar crystals are in the form of large prisms (but smaller than the pyroxene) and so the rock has a distinct 'black and white' appearance.

Only a very large thin section can give an adequate idea of the texture of the rock. Plate III, fig. 1 shows not only the two varieties but also the nature of the continuous transition of one into the other. A narrow intermediate zone is always present, and it is sometimes of a leucocratic character. In the coarse rock long prisms of pyroxene and felspar can be observed radiating into the band, with the micropegmatite occupying the space between the large crystals.

The texture is hypidiomorpho-granular holocrystalline. Both felspar and pyroxene appear either as hypidiomorphic or idiomorphic crystals, or in graphic intergrowth. Sometimes the same crystal is idiomorphic at one end and allotriomorphic at the other. Green uralitic and ordinary brown hornblende often fringe the pyroxene crystals. Iron-ore occurs in the form of granules and rods (plates). The groundmass is formed by micropegmatite and chlorite (palagonite). In sections rich in micropegmatite, free idiomorphic quartz may be found. Apatite is very abundant, especially in the mesostasis.

A very peculiar feature, observed in nearly all sections of this rock, is what one may call a micro-taxitic texture. The term 'taxitic

texture' was introduced by F. Loewinson-Lessing,[1] who defines it as follows: [2] 'Taxitic—alternation of areas of different composition and texture: (*a*) Eutaxitic—banded alternation of different areas, (*b*) Ataxitic—irregular, breccia-like alternation of different areas.'

In our case the irregularly distributed components are the micropegmatite and the pyroxene-felspar-pegmatite. There are patches of these two kinds of pegmatite. In places where the acid micropegmatitic patches (usually coloured red by minute flakes of haematite) reach a large size, the rock assumes a distinctly spotted appearance. But there is a perfect gradation between these true taxitic types to the microtaxitic type.

The coarse-grained rocks from all the localities mentioned above have been sliced and examined under the microscope, while the specimen from the Crook boring has been measured by means of Shand's micrometric stage and also analysed chemically. (Tables II and III.)

The *felspar* occurs mainly in the form of large stout prisms. As a rule it is quite fresh, except in the more acid varieties of the Whin Sill, where turbid felspar is prevalent (sericitized and saussuritized). Quite often it is idiomorphic, especially when surrounded by the micropegmatite. In the last case micropegmatite forms a radiating fringe round the felspar crystals. The felspathic component of the micropegmatitic fringe is always in optical continuity with the outer (albitic) rim of the phenocryst (Plate IV, fig. 3). In contact with pyroxene the felspar is often ragged. It encloses numerous needles of apatite and occasionally magnetite grains (in acid varieties, haematite). Albitic twinning is prominent, often combined with Carlsbad twinning or pericline cross lamination (probably secondary). The progressive continuous zoning, from calcic centre to sodic periphery, is well marked. This absence of rhythmic zoning is shared by the felspars of many igneous rocks which have developed free silica at the last stage of crystallization, as already noted by A. Harker. Although belonging to one generation, the felspar varies in composition within wide limits. The innermost portion corresponds to basic labradorite ($Ab_{35}An_{65}$), while the outer rim may attain the composition of oligoclase or even albite. The mean

[1] F. Loewinson-Lessing, Note sur les taxites et sur les roches clastiques volcaniques. Bull. Soc. Belge Géol., 1891, vol. 5, p. 103.

[2] F. Loewinson-Lessing and D. Beliankin, Petrographic Tables. (In Russian) 2nd edition, 1927, p. 76.

specific gravity (2·646) and the mean refractive index (from 1·545 to 1·560) seem to indicate that the felspar in its average composition corresponds to medium or basic andesine, and on the whole it appears to be slightly less calcic than the felspar from the medium-grained variety.

Table II.—Mineralogical composition of the coarse-grained variety of the Whin Sill (percentages by volume).

	Crook boring.	High Force.	Average Volume.	Average Weight.
Felspar	41·35	41·18	41·27	37·21
Micropegmatite	17·71	18·23	17·97	15·86
Quartz	2·80	2·76	2·78	2·47
Pyroxene	20·25	19·35	19·80	22·22
Hornblende, chlorite, &c. ...	10·54	9·72	10·13	9·20
Iron-ore	7·19	8·68	7·93	12·82
Iron-pyrites	0·16	0·08	0·12	0·22

Table III.—Chemical composition of the Whin Sill.

	I.	II.	III.
SiO_2	49·70	50·12	50·51
TiO_2	2·70	2·72	2·33
Al_2O_3	15·64	15·78	14·61
Fe_2O_3	2·42	2·44	3·50
FeO	11·35	11·46	8·85
CaO	8·03	8·10	8·76
MgO	3·06	3·09	5·32
MnO	0·14	0·14	0·22
Na_2O	2·90	2·92	2·55
K_2O	1·22	1·23	1·19
P_2O_5	0·55	0·55	0·31
FeS_2	0·24	0·24	0·50
CO_2	trace	—	—
H_2O (+110° C.) ...	1·20	1·21	1·35
H_2O (−110° C.) ...	0·70	—	—
	99·85	100·00	100·00

I. Coarse-grained variety of the Whin Sill. Crook boring, Co. Durham. Analysis by W. H. Herdsman.

II. Same, recalculated to 100 % (minus hygroscopic water).

III. Average of five analyses of the medium-grained variety of the Whin Sill: Caldron Snout (Teall), Borcovicus (Teall), Rotherhope (Finlayson), Snook Point (Smythe), Scordale Beck (Harwood).

Pyroxene. The predominant dark-brown pyroxene occurs in the form of long prismatic crystals, often curved and twisted. Although one may occasionally see broken pyroxene crystals with cracks sealed up by iron-ore, the curvature and twisting cannot be attributed to purely mechanical causes posterior to their formation.

In longitudinal sections perpendicular to the twinning plane (100) the basal parting appears in the form of fine striations, producing the typical 'herring-bone' structure (fig. 1). From the examination of several micro-sections the general impression is gained that this lamination is of a secondary origin. When highly developed it is often accompanied by a beautiful 'hour-glass' structure (plate IV, fig. 4), and also by a certain degree of alteration along the planes of lamination

Fig. 1. Pyroxene crystal (8 mm. long) with 'herring-bone' structure in the coarse Whin Sill, Crook boring. Co. Durham. Iron-ore, black; felspar, unshaded; hornblende, dark striation.

It may be that the two phenomena—lamination and 'hour-glass' structure—are closely connected, depending, as already suggested by Teall in reference to the lamination, on the water present in the mineral. Besides the alteration along the basal planes, the pyroxene crystals are often fringed by hornblende (green uralitic and normal brown variety).

Another interesting feature of the pyroxene is the frequent occurrence of the so-called 'polysomatic' structure, as defined by A. C. Lawson.[1] The 'polysomatic' crystals appear to be formed by a mosaic of areas having different optical orientation, while preserving their physical continuity, as defined by cleavage, &c.

The analyses of pyroxenes isolated from the coarse-grained variety of the Whin Sill by J. J. H. Teall show the presence of about 30 % of magnesium metasilicate molecule, but as the optical axial angle of this pyroxene is apparently normal, it cannot be called enstatite-

[1] A. C. Lawson, On the geology of the Rainy Lake region. Ann. Rep. Geol. Survey Canada, 1887, vol. 3.

augite. Typical ' enstatite-augite ' in the form of almost colourless, greatly decomposed prismatic crystals with a well-marked ' herring-bone ' structure is found sporadically in the coarse rock ; and, as in the medium-grained rock, it is an early product of crystallization. One may suppose that the ' enstatite-augite ' and the normal brown augite belong to the same genetic series. If so, we may represent the ferro-calc-magnesian reaction series as follows :

Olivine
↓ Discontinuity (resorbed)
Enstatite-Hypersthene
↓ Discontinuity (partly resorbed)
Clinoenstatite-Clinohypersthene
↓
Diopside-Hedenbergite
} Enstatite-Augite series (continuous).

This scheme apparently agrees with the interpretation of the process as proposed by A. Holmes, but it certainly fails to explain the early crystallization of augite as observed in certain sections of the fine- and medium-grained varieties. It may be that the scheme proposed is far too simple and that we have a separate branch of the augite series, along which crystallization began at an early stage and joining the enstatite-hypersthene branch lower down.

Pyroxene-felspar graphic intergrowth can be observed in nearly all specimens of the coarse-grained rock (plate IV, fig. 5). In places it can be even observed with the unaided eye. It occurs in definite taxitic patches alternating with patches of micropegmatite. The pyroxene of the intergrowth is either continuous with the large prismatic crystals (fig. 1) or is quite independent of them. The felspar of the intergrowth is definitely in optical continuity with the large crystals. Polysomatic structure is frequently observed in the pyroxene. Sometimes the intergrowth simulates the form of fucoid algae, similar to the so-called ' cervicorn ' type of intergrowths described by H. H. Thomas [1] (fig. 6).

The pyroxene-felspar intergrowth, although of rare occurrence in igneous rocks, has been described by many authors. As a rule it is confined to the coarse-grained varieties of quartz-dolerites or similar rocks. But the question of its origin and its relation to the ' gabbroidal eutectic ' has never been adequately discussed.

Micropegmatite is very abundant in the mesostasis, between the large crystals of pyroxene and felspar. Usually it forms a radiating

[1] H. H. Thomas, Geol. Survey Memoir on Mull, 1924, p. 333.

fringe round felspar crystals. The transverse section of this fringe gives a characteristic appearance of triangular and hexagonal areas of quartz.

Quartz occurs as large patches in places rich in micropegmatite, and usually it is in optical continuity with the quartz of the micropegmatite. It is, as a rule, allotriomorphic, but in acid varieties of the coarse Whin Sill it occurs in the form of fine idiomorphic crystals surrounded by palagonite.

Hornblende, *biotite*, and *chlorite* are found in the mesostasis. Biotite is sometimes seen replacing hornblende, and it was probably formed during the final stage of consolidation together with chlorite. The last mineral occurs in cloudy greenish masses associated with micropegmatite and also in the form of finely crystalline spheroidofibrous aggregates (palagonite). In places chlorite replaces felspar in the micropegmatite (fig. 8).

Apatite, in the form of very long slender needles, is very abundant, especially in the groundmass.

Iron-ore occurs in the form of large grains, granular clusters, and long narrow plates, frequently with a parallel arrangement. The majority of these plates are of early formation, but in certain places iron-ore is seen to cement broken crystals of pyroxene and fill cracks in pyroxene and felspar. We may therefore assume that the range of crystallization of the iron-ore was extensive. The presence of white bands of leucoxene and the data of the analysis show that we have here a titaniferous magnetite.

Iron-pyrites is found in small quantity, either as minute spongy spheroids or as infillings of minute cracks.

III. Certain Exceptional Varieties of the Whin Sill.

(1) *Red acid segregations.*

As has already been pointed out, even the normal coarse-grained rock has a tendency towards the development of a taxitic texture. Under certain favourable conditions this tendency resulted in the formation of a macro-taxitic rock with visible red spots. The attention of the author to this interesting variety has been drawn by Dr. J. A. Smythe, who is intending shortly to publish a special paper dealing with it. A fine example of this rock may be found in Gilderdale, near Alston. Under the microscope, this rock appears like the ordinary coarse Whin Sill, except for the fact that both

felspar and pyroxene are greatly decomposed (saussuritized and chloritized) and there is an abundance of a granophyric groundmass segregated in definite areas. A large amount of greenish material, together with hornblende and mica, is also present in the groundmass. Free quartz is abundant, and often it presents idiomorphic outlines against the chloritic mesostasis. This mesostasis is composed of a fibrous brownish-green chlorite. In its chemical composition (Table IV, analysis I) it differs greatly from the normal dolerite, being richer in silica, which is entirely due to the abundance of granophyric patches.

Table IV.

	I.	II.	III.
SiO_2	54·85	58·10	65·20
TiO_2	2·07	1·65	0·39
Al_2O_3	12·92	14·49	13·72
Fe_2O_3	0·88	—	3·63
FeO	12·51	9·51	3·72
CaO	7·87	5·05	2·79
MgO	2·62	3·32	1·01
MnO	0·08	0·16	—
Na_2O	2·57	2·76	5·22
K_2O	1·35	2·36	2·17
P_2O_5	0·57	0·73	0·38
FeS_2	0·11	—	—
CO_2	trace		—
H_2O (+110° C.) ...	1·63	1·61	1·27
H_2O (−110° C.) ...	0·21		0·72
	100·24 %	99·74	100·22
Sp. gr.	2·845	2·725	2·652

I. Whin Sill. Coarse-grained with red spots. Gilderdale, near Alston, Cumberland. Analysis by S. I. Tomkeieff. A partial analysis of another sample of the same rock gave SiO_2 56·85 and H_2O (+110° C.) 2·89 %.

II. Aplitic inclusions from the Whin Sill. Snook Point, Northumberland. Analysis by J. A. Smythe.

III. Felsite. Red veinlet in the Whin Sill. Alnwick Moor, Northumberland. Analysis by S. I. Tomkeieff.

Red acid veinlets are also found in many places in the Whin Sill. They are composed of a fine-grained felsitic rock almost entirely consisting of turbid acid felspar and micropegmatite. The red colour is apparently due to the presence of innumerable minute flakes of haematite. Unlike the red patches in the coarse rock, the red veinlets show a definite intrusive relation to the normal dolerite which they invade, but there is no distinct marginal chilling to be observed. In one place (Tindale quarry) a red veinlet was seen to

originate in a band of a coarse-grained slightly taxitic rock and continue into the surrounding medium-grained dolerite. Apparently the red veinlets represent a pure acid differentiate of the quartz-dolerite magma, subsequently injected into the solidified, but still hot rock (absence of marginal chilling). This differentiation took place in the coarse rock, and we can trace the successive stages of this differentiation from the micro-taxitic rock and through the macro-taxitic rock to the final squeezing out of the felsitic fraction and red-vein formation.

The chemical analysis of the red rock is given in Table IV, analysis III. It is a fairly acid rock almost corresponding to a granitic magma in composition. In comparison with the normal rock it is very rich in alkalis, and it is significant that the amount of Fe_2O_3 is actually greater than in the normal rock, which agrees well with the fact that the magnetic iron-ore is present in a very small amount and haematite has developed in its place.

(2) *Spheroidal aplitic inclusions.*

These inclusions have been described by J. A. Smythe [1] as occurring at Snook Point. They vary in size from $\frac{1}{8}$ to $\frac{7}{8}$ in. in diameter, and have a curious development of plates of iron sulphide (pyrrhotine) in their lower hemisphere, which produces a faceted appearance. The analyses of these inclusions as made by Smythe is given in Table IV (analysis II), and one can see that it is a fairly acid rock, having in composition an affinity to a syenitic magma (but somewhat poorer in alkalis). It occupies an intermediate position between the taxitic Whin Sill and the red veinlets.

Dr. Smythe was kind enough to place at the author's disposal a large number of micro-sections of these inclusions. They all show a sharp but continuous transition into the normal dolerite. All of them have large plates of pyrrhotine (and titanomagnetite) in the lower hemisphere. The rock of the inclusions is much finer in grain than the normal dolerite, and is characterized by the predominance of an acid felspar (rather turbid) and an almost complete absence of pyroxene, the place of which is taken by chlorite and hornblende. The rock could be called a doleritic aplite.

One section proved to be of particular interest (plate III, fig. 2). The nucleus is a pure aplitic rock largely composed of a turbid acid

[1] J. A. Smythe, Inclusions in the Great Whin Sill of Northumberland. Geol. Mag., 1914, dec. 6, vol. 1, pp. 244–255.

felspar (oligoclase or albite) with a scanty mesostasis of micropegmatite and chlorite and abundant apatite. It is surrounded by large plates of pyrrhotine with some titanomagnetite. Beyond the bordering plates lies the outer zone of the inclusion, which both in texture and composition is intermediate between the nucleus and the normal dolerite. Really we have here an inclusion within an inclusion. The transition of the outer zone into the surrounding normal dolerite is sharp but continuous, and marked by tangentially placed felspars.

There can be hardly any doubt that the inclusions are a product of differentiation of the quartz-dolerite magma. Dr. Smythe makes the suggestion that they may represent a remolten product of an early stage of crystallization. This is hardly possible, for an early product of crystallization would be at least as acid as the magma itself, if not more basic. Instead of this we may suggest that the inclusions are solidified globules of a fraction of the magma rich in volatiles and sulphur. This means that we have here a liquation-differentiation with a separation of one fraction in the form of liquid globules. Under the particular condition of chemical equilibrium in this fraction, iron separated in the form of large plates of pyrrhotine which sank to the bottom of the globule, leaving a portion richer in silica, which being more viscous formed a finer-grained aplite.

(3) *Pectolite inclusions.*

At Caw Burn, near Haltwhistle, the coarse-grained segregations occur in the form of spheroids up to 10 cm. in diameter. As a rule each of these segregations encloses at the top an eccentrically situated cavity infilled with a radial aggregate of pectolite. Pectolite also occurs independently of these spheroids in the vesicles in the normal dolerite and in veinlets. The coarse rock varies from a normal gabbroid variety with large pyroxene crystals exhibiting a fine schiller lustre, to a light-greenish leucocratic rock very rich in pectolite in its groundmass. Microscopically, the dark variety of the coarse rock is similar to that found elsewhere, with a pyroxene showing a perfect 'hour-glass' structure (fig. 4) and a well-developed basal lamination. The felspar is greatly seriticized and saussuritized. In the leucocratic variety the pyroxene is less abundant and mostly found in graphic intergrowth with felspar. There is also more acid felspar present and very little micropegmatite in the groundmass, the place of which is taken by a fibrous pectolite, which can also be

seen to encroach on felspar. Small laths of green hornblende are often found embedded in pectolite. It is highly pleochroic and has a small extinction-angle, and is perhaps arfvedsonite. In places, the hornblende laths are embedded in a finely-radiating non-pleochroic palagonite. Pectolite from this locality has been analysed by J. A. Smythe.[1]

What is the origin of pectolite in the Whin Sill? That hydrous silicates are formed during the last period of consolidation of an igneous rock is a well-known fact and need not be discussed here, but how are we to explain the presence in the vesicles of many minerals rich in calcium? In the normal course of crystallization of the basaltic magma the calcium-rich minerals crystallize out first so as to leave a more alkaline residue. It may be that calcium is retained by the hydro-gaseous phase of the magma, or that the calcium-rich hydrous silicates are produced through the reaction between the previously-formed calcium silicates and water-vapour, or, finally, that they are formed through assimilation of limestone by the magma. The data of our observations is insufficient to solve this problem.

IV. The Specific Gravity.

A new set of specific gravity determinations of the different varieties of the Whin Sill was obtained by the author by means of a hydrostatic balance and corrected to 4° C. The rocks are grouped according to the classification outlined above, i. e. into: (1) Fine-grained (contact facies); (2) Medium-grained (dolerite); (3) Coarse-grained (gabbro).

Locality.	1.	2.	3.
Crook boring	—	3·015	2·863
,, ,, ...	—	3·010	2·871
,, ,, ...	—	3·033	2·932
,, ,, ...	—	3·010	2·948
,, ,, ...	—	3·013	2·951
Middleton in Teesdale	2·938	2·958	2·941
Blea Beck (Teesdale)	2·896	—	—
High Force (quarry)	—	2·983	2·960
,, ,, (waterfall)	2·884	2·927	—
Langdale Beck	—	2·952	2·948
Maize Beck	—	2·947	2·923
Caldron Snout	—	2·941	2·920
,, ,, ...	—	2·976	3·020

[1] J. A. Smythe, Minerals of the north country: silicates. The Vasculum, Newcastle-upon-Tyne, 1924, vol. 10, p. 100. [Min. Abstr., vol. 3, p. 25.]

Locality.	1.	2.	3.
Tyne Head...	—	2·944	2·978
,, ,, ...	—	—	3·104
Hargill Beck	—	2·908	—
Lune Moor...	—	2·945	—
Gilderdale, normal	2·942	2·952	3·004
,, ,, ...	2·960	—	2·990
,, few pink spots ...	—	—	2·935
,, rich in pink spots ...	—	—	2·845
,, ,, ,, ...	—	—	2·831
Black Burn	2·933	3·039	2·958
Copt Hill	3·028	3·002	—
Stanhope (Little Whin Sill) ...	—	2·996	—
Caw Burn	—	2·996	2·976
Craig Lough	—	2·943	—
Borcovicus...	2·880	2·965	—
Average	2·933	2·975	2·944

We see that on the average the coarse-grained variety is lighter than the medium-grained variety.

V. On the Genesis of the Coarse-grained Variety of the Whin Sill and Acid Segregations, and its Bearing on the Question of Magmatic Differentiation.

The quartz-dolerites are widely spread in space and time. They always occur in the form of sills and dikes, and usually present the same petrographical characters as the Whin Sill. Almost everywhere these rocks exhibit bands or patches of coarse gabbroidal rock, as a rule sharply separated from the normal dolerite. The coarse rock from many various localities shows the same marked development of micropegmatite with a tendency to patchy segregation, as in the Whin Sill. Sometimes a pyroxene-felspar intergrowth is also to be found, and also acid veinlets within the body of the normal dolerite. This world-wide similarity of quartz-dolerites and their varieties is most striking. They have been recorded and described, besides in England and Scotland, in Sweden, Russia, France, India, Congo, South Africa, British Guiana, U.S.A., Canada, Australia, Antarctica, &c. It would be impossible to give here all the numerous references, but it is amazing how the description of certain quartz-dolerites from New England (Trias), British Guiana (Cretaceous), and Canada (pre-Cambrian) could be matched by those of the Whin Sill.

Chemically, all these rocks belong to one definite magmatic type, which is, as a matter of fact, nothing else than the 'plateau basalt'

magma type (excluding the extreme olivine-basalt sub-type), as the analyses compiled by H. S. Washington show.[1] We may assume, therefore, that the quartz-dolerite magma is the hypabasal representative of the primary ' plateau-basalt ' magma.

Our study of the Whin Sill, and especially its products of differentiation, may therefore throw some light on a wider problem of petrogenesis. First we shall discuss the genesis of the coarse bands.

As the comparison of the chemical analyses shows (Table III), the coarse rock does not differ much in its chemical composition from the normal dolerite. There are some minor differences, such as the content of FeO and MgO being respectively higher and lower than in the normal rock, but contrary to all expectation the silica percentage is even slightly lower in the coarse rock, although this small difference in silica content has no real significance. The essential difference of the two varieties apart from the texture lies in the mineral composition. The following table shows this quite clearly :

	Medium-grained variety.		Coarse-grained variety.	
Felspar	51·28	51·28 %	37·21	55·54 %
Micropegmatite ...	—		15·86	
Quartz	—		2·47	
Pyroxene	34·05	38·60	22·22	31·42
Hornblende, &c. ...	4·55		9·20	
Iron-ore	10·12		13·04	

In the coarse rock the leucocratic portion is more abundant, and this is mainly due to the development of quartz. An early withdrawal of iron from the magma in the form of iron oxide and also in a larger quantity (there is more of the iron-ore in the coarse rock) is probably one of the causes for the appearance of free silica in the coarse rock. This silica in the normal course of crystallization would probably form an iron metasilicate as part of the pyroxene molecule. This is why we also see a corresponding decrease in the amount of melanocratic silicates in the coarse rock. The amount of pyroxene is still further reduced by the higher development of hornblende, mica, and chlorite. In this way we see that the different mineral composition of these two rocks can be balanced against their identical chemical composition, and so we may apply to them the term ' heteromorphic ' as proposed by Lacroix.

[1] H. S. Washington, Deccan traps and other plateau basalts. Bull. Geol. Soc. Amer., 1922, vol. 33, p. 765.

There may be many hypotheses advanced to explain the origin of heteromorphic rocks, but we can at the outset dismiss some of them. First we may dismiss the hypothesis which would explain the genesis of the coarse bands by the squeezing out of the residual liquor (filter pressing). Besides a total absence of textural evidence in favour of this hypothesis, the chemical identity of the two rocks speaks against it. The same applies to the hypothesis of a latter injection, which was once applied to explain the origin of banded gabbro of Skye, but was rejected by Geikie and Teall,[1] who sought the cause of banding in the heterogenity of magma prior to injection. After having excluded the above hypotheses, let us consider the probable causes which led to the formation of the coarse dolerite-pegmatite. Generally speaking the grain-size in an igneous rock depends on three principal factors, viz. (1) chemical composition of the magma, (2) rate of cooling, and (3) viscosity of the magma. As a matter of fact, the last of the three factors is closely bound up with the first.

In our case the chemical composition and the rate of cooling must have been the same for both varieties. We have therefore to suppose that the coarse rock was crystallized out of a magma of lower viscosity. It is a well-known fact that the presence of even a small amount of volatiles greatly lowers the viscosity of the magma. Besides the evidence derived from the consideration of texture, the abundance in the coarse rock of hydrous minerals, such as chlorite, mica, hornblende, as well as micropegmatite, speaks in favour of this view. E. V. Shannon, who has described a dolerite-pegmatite from a sill at Goose Creek, Virginia, a rock remarkably similar to the coarse variety of the Whin Sill, thinks that 'it owes its peculiar feature to concentration of volatile constituents, notably water, into spots of greater or less size which remained fluid after the main mass of the diabase solidified and permitted the growth of large crystals producing unusually coarse texture'.[2] In his valuable paper he also discusses numerous other occurrences of dolerite-pegmatite described in American literature.

The only way to explain the formation of patches of magma rich

[1] A. Geikie and J. J. H. Teall, On the banded structure of some Tertiary gabbros in the Isle of Skye. Quart. Journ. Geol. Soc. London, 1894, vol. 50, p. 645.

[2] E. V. Shannon, The mineralogy and petrology of intrusive Triassic diabase at Goose Creek, Loudoun County, Virginia. Proc. U.S. Nat. Mus., 1924, vol. 66, art. 2, pp. 17–18.

in volatiles (including water) is by postulating a sort of liquation-differentiation within the body of the magma prior to its injection into the strata. Possibly this 'wet' differentiation formed in the intercrustal basin was caught up by the ascending magma and stretched out in the form of lozenge-shaped tabular bodies parallel to the walls of the injection chamber. These 'wet' portions were affected by cooling in the same way as the surrounding normal magma, but being more fluid they crystallized more freely, with the formation of long crystals of pyroxene and felspar. The combined effect of the volatiles and the rate of crystallization resulted also in a different physico-chemical equilibrium leading to a formation of a heteromorphic rock.

Certainly there is nothing new in the liquation-differentiation hypothesis, which is supported by such authorities as F. Loewinson-Lessing and R. A. Daly, although at the present time it finds many opponents among petrologists. Geikie and Teall evidently had this idea in mind when they wrote, that 'we therefore conclude that the cause which produced the banding must have operated before the crystallization of the minerals from the igneous magma'.[1] Harker[2] also thinks that the banded gabbros of Skye have originated through the injection of a heterogeneous magma, and Loewinson-Lessing uses the term 'macro-emulsional' magma in explaining the origin of banded gabbros in the Ural Mountains.[3]

It would be as well to explain here that in postulating a liquation of magma we do not imply a perfect immiscibility of the fractions, such as that of the sulphide fraction in a molten slag. The immiscibility of the fractions must be regarded more as a type of limited miscibility, conditioned by the factors of temperature, pressure, and time. The volatiles might concentrate in a certain part of the magma reservoir and form a 'wet' fraction which, although not absolutely immiscible with the rest of the magma, when caught up by the normal magma during injection would remain separated from it, simply because the crystallization would take place before such mixing could be accomplished. This relative immiscibility, therefore, is only conditioned by the time factor. An analogy is given by a mixture of porridge and milk, which on stirring at first forms

[1] A. Geikie and J. J. H. Teall, loc. cit., 1894, p. 653.

[2] A. Harker, The Tertiary igneous rocks of Skye. Mem. Geol. Survey, 1904.

[3] F. Loewinson-Lessing, Geological description of the Youjno-Saoserskaya dacha and Denishkin kamen. Trav. Soc. Nat. St.-Pétersbourg, 1900, vol. 30, livr. 5.

stringers of a milk-rich portion in a thick portion, and only after a certain time becomes perfectly homogeneous.

As seen from its finished product—the coarse dolerite-pegmatite —the 'wet' fraction is characterized by its own sequence of crystallization. Apparently under 'wet' conditions there is less affinity between the iron oxides and silica, and this results in an increased formation of iron-ore and liberation of free silica, which at the last stage of crystallization formed a micropegmatitic intergrowth with the alkali felspar. Theoretically, in the 'wet' portion a more perfect equilibrium must be attainable than in the 'dry' portion, due to the absence of super-saturation, under-cooling, &c. This is probably why we observe here several eutectics (or eutectoids), such as the intergrowths of quartz-orthoclase-albite, pyroxene-felspar, orthorhombic and monoclinic pyroxenes, and magnetite-ilmenite.

The peculiar course of crystallization in the 'wet' fraction also explains the origin of red patches and acid veins. Whereas in the normal doleritic magma hardly any acid residual liquor is formed at the last stage of crystallization, in the 'wet' fraction we observe a marked movement of the liquidus towards the acid pole. The taxitic texture so prevalent in the coarse rock is due to the tendency of the acid liquidus to segregate in definite spots. Under favourable conditions the acid liquor can even be squeezed out into cracks in the surrounding rock, with the resulting formation of aplitic and felsitic veinlets. Apparently under certain conditions the separation of the acid portion can take place while the magma is still liquid (magmatic emulsion), so that the blobs of the acid differentiate on cooling form the spherical inclusions described by Dr. Smythe.

In this way we can follow in the coarse Whin Sill all the stages of differentiation from the formation of a micro-taxitic rock through a typical taxite (spotted rock) to the separation of granophyric portion in the form of red veinlets. The degree of separation depends, not only on the viscosity of the magma, but also on the time during which it cooled. In large intercrustal magmatic reservoirs, therefore, we may expect a greater and more complete differentiation of the quartz-dolerite magma with the resulting formation of olivine-gabbro and granophyre. This large-scale differentiation certainly cannot be attained by filter-pressing alone; it may be the combined effect of liquation- and crystallization-differentiations, and only in certain favourable circumstances accentuated by the filter-pressing. It would be impossible with certainty to apply directly the process of

differentiation as observed in the Whin Sill to this great petrogenetic problem, but one must not forget that similar causes are in operation whether we are considering small or large phenomena in nature.

In conclusion I would like to thank Prof. A. Holmes for his kind help and friendly discussion of the problems involved in this paper, without making him responsible for any of the views expressed in it; Dr. J. A. Smythe for the loan of micro-sections of the inclusions and the specimen of the taxitic rock from Gilderdale; and also to all my colleagues of the Geological Department of Armstrong College for their friendly advice and co-operation.

Explanation of Plates III and IV.

Fig. 1. Whin Sill, coarse-grained variety passing into the medium-grained variety. Crook boring, Co. Durham.

The upper portion shows the coarse rock (*a*) with large crystals of felspar and pyroxene radiating into the band, and the micropegmatitic mesostasis filling up the lacunae. A narrow transition zone (*b*) separates this rock from the normal medium-grained dolerite (*c*) with sub-ophitic augite and small felspar laths. Ordinary light. ×20.

Fig. 2. Inclusion in the Whin Sill. Snook Point, Northumberland.

(*a*) Acid nucleus composed of a meshwork of turbid acid felspar, micropegmatite, some hornblende and apatite. It is surrounded by large plates of pyrrhotine. (*b*) Outer zone of the inclusion, of a slightly coarser texture than the nucleus, in which the ferromagnesian minerals (mainly chlorite) are more developed. (*c*) Normal medium-grained dolerite surrounding the inclusion. Ordinary light. ×15.

Fig. 3. Whin Sill, coarse-grained. Crook boring, Co. Durham.

Felspar phenocrysts with a continuous zonal structure in a groundmass of micropegmatite. The outer acid zone of the phenocrysts is continuous with the felspar of the micropegmatite and has straight extinction. The extinction-angle of the inner portion is 18°. Nicols crossed. ×25.

Fig. 4. Whin Sill, coarse-grained. Caw Burn, Northumberland.

'Hour-glass' structure of pyroxene. Section approximately perpendicular to the *c*-axis, so that the basal lamination is not shown. Ordinary light. ×22.

Fig. 5. Whin Sill, coarse-grained. Crook boring, Co. Durham.

Pyroxene-felspar intergrowth. Ordinary light. ×25.

Fig. 6. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Pyroxene-felspar intergrowth, 'cervicorn' type. Ordinary light. ×30.

Fig. 7. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Semi-idiomorphic crystal of quartz embedded in a finely fibrous palagonite. A plate of titaniferous iron-ore traverses the section. The remainder is made up of decomposed felspar, pyroxene, and micropegmatite. Ordinary light. ×22.

Fig. 8. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Palagonite replacing felspar in the micropegmatite. Ordinary light. ×25.

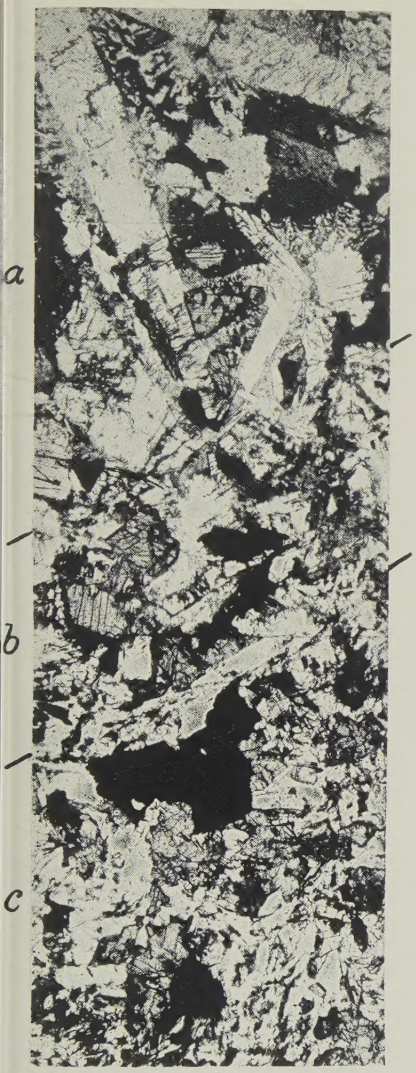


Fig. 1

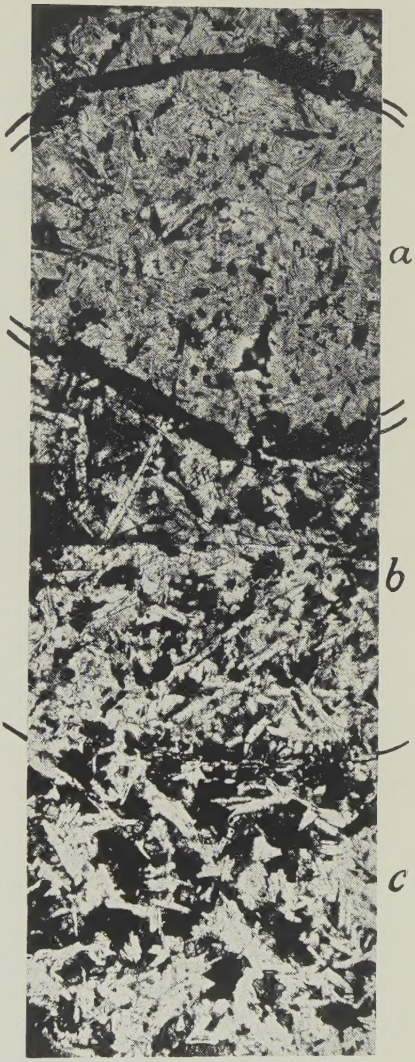


Fig. 2

S. I. Tomkeieff: The Whin Sill

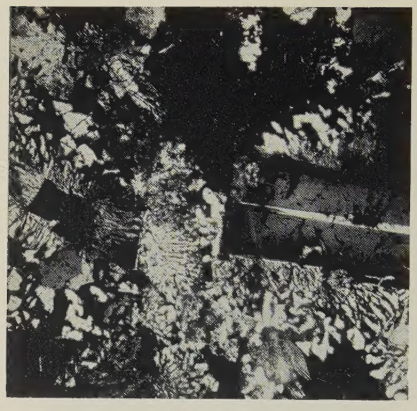


Fig. 3

Fig 4

Fig. 5

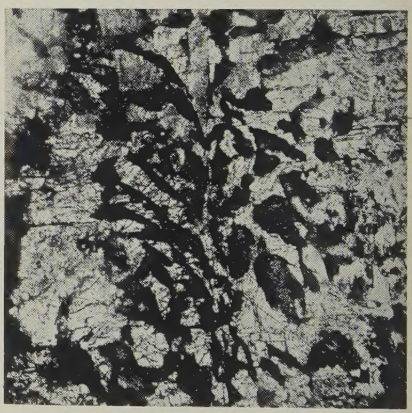


Fig. 6

Fig. 7

Fig. 8

S. I. Tomkeieff: The Whin Sill

PUBLICATIONS

OF THE

MINERALOGICAL SOCIETY

The Publisher is Mr. Humphrey Milford, Oxford University Press, *Amen House, Warwick Square, London, E.C.* 4.

Mineralogical Magazine.—Current Numbers price 6*s.* net each. Annual Subscription for four Numbers post free 20*s.*, payable in advance to the Publisher, either direct or through any bookseller.

Back Numbers.—With the exception of Nos. 17, 18, 19, 21, and 22, which are out of print (and some few numbers of which the stock is low and which are reserved for the sets mentioned below), all numbers can be supplied separately at the following net rates: Nos. 1–48 at 4*s.* each; Nos. 49–111 at 5*s.* each; Nos. 112 (1926) onwards at 6*s.* each. Since 1920 (Vol. XIX) the Numbers have been issued quarterly, and include a separately-paged appendix of *Mineralogical Abstracts.*

Geological Map of the Shetland Islands (separate from Vol. II). Price, 4*s.* mounted, 2*s.* 6*d.* unmounted, net.

General Index to Vols. I–X, 4*s.*; to Vols. XI–XX, 6*s.* net.

Mineralogical Abstracts (Vol. I, Nos. 1–12, 1920–22, issued with Vol. XIX of the Magazine) are also sold separately. Price 2*s.* 6*d.* net each number. Later numbers (Vol. II, 1923–25; Vol. III, 1926–28; Vol. IV, 1929–) are issued only as part of the Magazine.

Bye-Laws and List of Members. Price 1*s.* net.

Part sets at the following reduced rates. Set A.—Vols. I–X (Nos. 1–48, 1876–94, and Index No.) at 4*s.* per number less 15% (to Members of the Society less 35%). Set B.—Vols. XI–XX (Nos. 49–111, 1895–1925, and Index No.) at 5*s.* per number less 15% (to Members less 35%). Set C.—Vols. I–XX (Nos. 1–111 and two Index Nos.) at the above initial prices less 20% (to Members less 40%).

Proceedings of the Crystallological Society [amalgamated with the Mineralogical Society in 1883]. Parts I and II (1877, 1882), price 4*s.* net each.

GENERAL NOTICES

Members desiring to propose Candidates for Election are requested to send the names and qualifications of the Candidates to the General Secretary, W. Campbell Smith, M.C., M.A., F.G.S., *Natural History Museum, South Kensington, London, S.W.* 7. There is an entrance fee of one guinea and the annual subscription is one guinea; the latter can be compounded for by a single payment of fifteen guineas. New Members, on the payment of their first subscription, receive all the numbers of the Magazine for the year for which the subscription is paid.

There are four meetings of the Society each year, on Tuesdays at 5.30 p.m. in January, March, June, and November. They are held (by kind permission) in the Apartments of the Geological Society, Burlington House, Piccadilly, London, W. 1. Titles of papers to be read at these meetings, with a view to subsequent publication in the Magazine, should be sent to the General Secretary at least two weeks before the meeting. Authors alone are responsible for the views set forth in their respective papers. They are allowed, free of charge, fifty separate copies of their papers published in the Magazine.

MINERALOGICAL MAGAZINE

CONTENTS OF NO. 125

(June, 1929)

PAGE

C. E. Tilley: On larnite (calcium orthosilicate, a new mineral) and its associated minerals from the limestone contact-zone of Scawt Hill, Co. Antrim 77

T. V. M. Rao: 'Bauxite' from Kashmir 87

A. W. Groves and A. E. Mourant: Inclusions in the apatites of some igneous rocks 92

S. I. Tomkeieff: A contribution to the petrology of the Whin Sill. (With Plates III and IV) 100

MINERALOGICAL ABSTRACTS

(Vol. 4, No. 2, Pages 49–96)

Bibliographies (p. 49).—Mathematical Crystallography (p. 52).—Crystal-optics (p. 55).—Physical Properties of Crystals (p. 59).—Precious Stones (p. 67).—Economic Minerals and Ore-deposits (p. 73).—Miscellaneous (p. 81).

	PAGE		PAGE		PAGE		PAGE
Adams, L. H.	65	Fersman, A. E.	72	Laby, T. H.	61	Schmidt, W.	55
Aminoff, G.	89	Geier, B.	77	Lacroix, A.	49	Schubnikoff, A.	65
Baier, E.	55	Geilmann, W.	76	Larsen, E. S.	89, 90	Seifert, H.	64, 88
Barker, T. V.	54	Giannotti, C.	55, 82	Laufer, B.	71	Sesta, L.	68
Barwick, G. F.	50	Gibson, R. E.	66	Lindgren, W.	51	Shannon, E. V.	83, 91
Bauer, L. H.	90–1	Gonyer, F. A.	83	Lingen, J. S. van der	83	Shubnikov, A.	65
Becke, F.	54	Griffiths, E.	61	Livens, G. H.	57	Šimáně, J.	75
Berman, H.	90–1	Haase, M.	58	Lonsdale, J. T.	96	Sjögren, H.	89
Billiet, V.	96	Hall, A. L.	51	Lowry, T. M.	56	Slavík, F.	74, 82
Bracewell, S.	70	Harbich, E.	87	Lunde, G.	78	Spencer, L. J.	50, 66, 72
Bradshaw, T.	57	Harger, H. S.	68	MacCarthy, G. R.	96	Stamm, P.	57
Brandenberger, E.	52	Harris, F. C.	57	Macgregor, A. M.	80	Swaminathan, V. S.	85
Brewer, F. M.	88	Harvey, R. D.	61	McLennan, J. C.	61	Syromyatnikov, F. V.	64
Bridgman, P. W.	65	Hatch, F. H.	73	Mandell, W.	62–3	Terpstra, P.	56, 63
Buerger, M. J.	64	Heide, F.	88	Matthes, O.	88	Thompson, L. S.	70
Bultingaire, L.	49	Herlinger, E.	55	Merensky, H.	69	Thomson, E.	94–5
Carmichael, F.	94	Hermann, C.	53	Middlemiss, C. S.	78	Tilley, C. E.	84
Chaudron, G.	60	Herroun, E. F.	59, 60	Mügge, O.	63	Ulrich, F.	74
Christie, W. A. K.	86	Holland, T. H.	52	Nickles, J. M.	50–1	Van der Lingen, J. S.	83
Church, A. H.	67	Holt, D. A.	88	Niggli, P.	52–3	Van Horn, F. R.	96
Cohen, E.	61	Howarth, W. E.	84	Nishio, S.	87	Vavrinecz, G.	81
Coode-Adams, W. R. C.	56	Huggett, J.	60	North, F. J.	84	Veselý, V.	74
Coulson, A. L.	86	Hunt, W. F.	50	Palache, C.	66, 90–2	Vlodavetz, N. I.	78
D'Achiardi, G.	82	Hurst, M. E.	79	Papish, J.	88	Wagner, P. A.	69
Desch, C. H.	68	Ito, T.	53	Parsons, A. L.	85, 94	Walker, T. L.	94
Doty, M. F.	51	Jack, R. L.	77	Partridge, E. P.	85	Wheeler, R. E. M.	67
Draper, D.	68	Ježek, B.	82	Peacock, M. A.	92	Wherry, E. T.	54
Eardley-Wilmot, V. L.	79	Johnson, M.	78	Philipsborn, H.	84	Wild, G. O.	72
Ehrenberg, H.	76	Jourdan, C. J. N.	93	Poindexter, O. F.	69	Wilder, F. A.	89
Elam, C. F.	63	Kallauner, O.	75	Ramsdell, L. S.	85	Wilson, E.	59, 60
Elings, S. B.	63	Kani, K.	87	Rastall, R. H.	73	Wilson, M. E.	79
Ellsworth, H. V.	90, 95	Kannuluik, W. G.	61	Richards, G.	89	Wlodawetz, N. I.	78
Emmons, R. C.	58	Kato, T.	73	Rinne, F.	53, 58, 70	Woyno, T. J.	58
Ernst, E.	53	Keep, F. E.	80	Rogers, A. F.	54, 95	Yamaguchi, K.	87
Fairbanks, E. E.	96	Kinoshita, K.	86	Rose, H.	76	Yoshiki, B.	86
Farrington, O. C.	71	Kittl, E.	51	Ruedy, R.	61	Želízko, J. V.	76
		Klemm, R.	72	Rumbold, W. G.	78		
		Krauss, F.	67	Schaller, W. T.	93		
		Krenner, J.	81	Schiebold, E.	53		
		Kunz, G. F.	67				

First printed in Great Britain, at the University Press, Oxford

Reprinted by photo-litho by Alden & Mowbray Ltd.

at the Alden Press, Oxford, 1970